DESIGN, CONSTRUCTION AND EVALUATION OF PERFORMANCE OF SOLAR DRYER FOR DRYING FRUIT

By

Tiruwork Berhanu Tibebu

A Thesis Submitted to the Department of Agricultural Engineering, Kwame Nkrumah University of Science and Technology in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Bioengineering

College of Engineering

September 2015

DECLARATION

I hearby declare that this submission is my own work towards the M.Sc. and that, to the best of my knowledge, it contains no material previously published by another person nor material which has been accepted for the award of any other degree of the University, except where due acknowledgment has been made in the text.

Tiruwork Berhanu Tibebu ……………………… …………………….
(ID PG9818913) Signature Date
(Student)

Certified by:

Prof. Ebenezer Mensah ……………………… ……………………..
(Supervisor) Signature Date

Dr. George Y. Obeng ……………………… ……………………..
(Supervisor) Signature Date

Prof. Ato Bart-Plange ……………………… ……………………..
(Head of Department) Signature Date

ACCKNOWLEDGMENT

First and foremost I would like to thank God for everything he has done for me and for the courage and strength he gave me. I am also thankful to my supervisors Prof. Ebenezer Mensah and Dr. George Y. Obeng for their support and guidance throughout my project.

My gratitude goes to all those who helped me in the construction of the design. I like to thank Technology Consultancy Centre (TCC) KNUST, MIT D-Lab IDIN Project, Amy Smith, Mr. Joseph O. Akowuah, Mr. Emmanuel Amankwah, Mr. Edwin Adjei and Mr. Koffi for giving me the necessary equipment for accomplishing this project.

I would also like to appreciate Intra-ACP mobility scholarship. My education was successfully achieved by funding from this scholarship and a continuous follow up and help from the KNUST coordinator, Mr. Ernest Adu-Gyamfi.

Finally, I am thankful to my family and friends for their support and encouragement.

ABSTRACT

An indirect type solar dryer integrated with a charcoal burning stove that can be used for drying fruits was designed, constructed and evaluated. The study mainly tried to address the problem associated with the fact that solar dryers are efficiently operational only when there is sufficient solar energy. Hence, an additional means of supplying heat was included so that drying can be made continuous during the night time and in rainy seasons.

The dryer mainly consists of a solar collector panel, drying chamber, chimney and a charcoal stove. The solar collector is made up of 5 mm thickness single layer glass, 2 mm black painted aluminum absorber plate and 3 mm fiber glass insulation which is enclosed in a casing made from wood. The drying chamber is made from plywood with 2 cm thickness. Galvanized metal sheet of 1 mm thickness was rolled and welded to make the chimney. The backup heater uses a stove commonly known as "Gyapa" stove to burn charcoal and supply heat to the drying chamber. The total cost of the dryer was estimated to be GhC 1047.00 (US$ 327.00*).

Different tests were carried out in order to evaluate the performance of the dryer. No load test, i.e. test without keeping any material to be dried, was performed and it indicated temperature could rise up to 53.3 ^{o}C in the dryer. Average collector temperature recorded was 56.4 ^{o}C. In the evening, the dryer temperature was kept above the ambient and collector temperature by burning charcoal using the backup stove. As a result, after three hours of heat supply the drying temperature reached 50.8 ^{o}C.

* 1 USD = 3.2 GhC (as of February 2015)

The dryer performance was also evaluated using pineapple and mango. For the different tests carried out the performance parameters used for evaluation included moisture content, drying rate and drying efficiency.

The moisture content of pineapple and mango was reduced from 87 % and 85 % to 16 % and 13 %, respectively, within two to three days. When using only solar energy as a heat source, the drying rate for pineapple was found to be 23.7 g/h whereas for mango it was 15.5 g/h. These values were found to be 25.2 g/h and 18.4 g/h, for pineapple and mango, respectively, when solar drying was performed with the backup heater (heater used in the evening only). But a higher drying rate was obtained, 32.5 g/h for pineapple and 19.3 g/h for mango, when the backup heater was used with the solar energy during both the day time and in the evening. The collector efficiency was found to be 31.7 %. Drying efficiency was also found to be 9.7 %, 7.5 % and 8.7 % for solar drying, hybrid mode (backup heater used in the evening) and solar drying in hybrid mode (backup heater used during day time and evening), respectively.

TABLE OF CONTENTS

Title Page i

Decleration ii

Accknowledgment iii

Abstract iv

List of Tables x

List of Figures xi

CHAPTER ONE: INTRODUCTION 1

1.1. Background 1

1.2. Problem Statement 2

1.3. Justification 3

1.4. Research Objectives 3

1.4.1.Specific Objectives 4

CHAPTER TWO: LITERATURE REVIEW 5

2.1. Sun Drying 6

2.2. Solar Drying 7

2.3. Types of Solar Dryers 8

2.3.1. Direct Solar Dryers 8

2.3.2. Indirect Solar Dryers 14

2.3.3. Mixed Mode Solar Dryers 17

2.4. Hybrid Solar Dryers 21

2.5. Solar Dryers with Concentrators 23

2.6. Materials Used for Constructing Solar Dryers 26
2.7. Gaps Identified in the Review 30
2.8. Components of Solar Dryers 32
2.8.1. Solar Collector 32
2.8.2. Drying Chamber 33
2.8.3. Chimney 34
2.9. Performance Evaluation of Dryers 34
2.9.1. Collector Efficiency 34
2.9.2. Drying Efficiency 35
2.9.3. Drying Rate 35
2.9.4. Moisture Content 36
CHAPTER THREE: MATERIALS AND METHODS 37
3.1. Design Procedure 37
3.1.1. Drying Temperature 37
3.1.2. Amount of Moisture to be Removed 38
3.1.3. Heat Energy Required to Remove Water 38
3.1.4. Sizing the Collector 40
3.1.5. Collector Orientation and Tilt Angle 41
3.1.6. Air Flow Requirement 41
3.2. Construction of the Solar Dryer 42
3.2.1. Collector 42
3.2.2. Drying Chamber 43
3.2.3. Chimney 43
3.2.4. Backup Heater 44
3.2.5. Drawing of the Dryer 44

3.2.6. Cost of Dryer 47
3.3. Experimental Procedures and Dryer Evaluation 48
3.3.1. Material Preparation for Drying 48
3.3.2. Instruments Used for Data Collection 48
3.3.3. Dryer Evaluation Tests 49
3.3.3.1. No Load Test 49
3.3.3.2. Solar Drying Test 50
3.3.3.3. Solar Drying in Hybrid Mode Test: Backup Heater used only in the Evening 51
3.3.3.4. Solar Drying in Hybrid Mode Test: Backup Heater used during Day Time and in the Evening 51

CHAPTER FOUR: RESULTS AND DISCUSSION 52
4.1. No Load Test 52
4.2. Solar Drying Test 54
4.3. Solar Drying in Hybrid Mode: Backup Heater used only in the Evening 58
4.4. Solar Drying in Hybrid Mode: Backup Heater used During Day Time and in the Evening 63
4.5. Drying Rate 67
4.6. Collector Efficiency and Drying Efficiency 68

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS 71
5.1. Conclusion 71
5.2. Recommendations 72
REFERENCES 73

APPENDIX 1: Sample Analysis of Moisture Content 80
APPENDIX 2: Typical Temperature and Humidity Variation with time During No-Load Test 84
APPENDIX 3: Solar Insulation, W/m^2 (Solar Lab, KNUST) 85
APPENDIX 4: Chemical Composition of Fresh pineapple and mango 86
APPENDIX 5: Gyapa stove Sizes, Dimensions and Applications 87
APPENDIX 6: Cost of the Solar Dryer 88

LIST OF TABLES

TABLES **PAGE**

Table 2.1. Material Usage 27
Table 2.3. Summary of Gaps Identified in the Review.. 31
Table 4.1. Drying rate of pineapple and mango for the different drying modes. 67
Table 4.2. Drying rate of pineapple and mango in terms of the dry solid matter for the different drying modes. ....
68 Table 4.3. Drying Efficiency for different drying modes. ....
70 **LIST OF FIGURES**

FIGURE **PAGE**

Fig. 2.1. Schematic Diagram of Sun and Solar Drying. 7
Fig. 2.2. Cabinet Dryer 9
Fig. 2.3. Tent Dryer.. 10
Fig. 2.4. Pictorial View of Cabinet Dryer 11
Fig. 2.5. Forced Convection Direct Mode Solar Dryer.. 13
Fig. 2.6. Sketch of Indirect Solar Dryer 15

Fig. 2.7. Indirect Solar Dryer 16

Fig. 2.8. Mixed Mode Solar Dryer 18

Fig. 2.9. Mixed Mode Solar Dryer 20

Fig. 2.10. Solar-Biomass Hybrid Cabinet Dryer.. 22

Fig. 2.11. Solar crop dryer and concave solar concentrator 25

Fig. 2.12. Solar dryer with two solar concentrating panels 26

Fig. 3.1. Dryer drawing 45

Fig. 3.2. Side view of the dryer 46

Fig. 3.3. Pictorial view of the constructed dryer. 47

Fig. 4.1. Temperature variation with for no load test. 52

Fig. 4.2. Moisture loss (wet basis) by pineapple with time 54

Fig. 4.3. Moisture loss (dry basis) by pineapple with time 54

Fig. 4.4. Variation of moisture content (w.b.) with time by mango. 56

Fig. 4.5. Variation of moisture content (d.b.) with time by mango. 56

Fig. 4.6. Moisture loss of mango and pineapple with time. 58

Fig. 4.7. Variation of temperature with time by backup heater in the evening. 59

Fig. 4.8. Variation of relative humidity with time of backup heater used in the evening. 60

Fig. 4.9. Variation of moisture content (w.b) with time of pineapple using backup heater in the evening. 61

Fig. 4.10. Variation of moisture content (d.b) with time of pineapple using backup heater in the evening. 61

Fig. 4.11. Variation of moisture content (w.b) with time for mango when backup heater is used in the evening. 62

Fig. 4.12. Variation of moisture content (d.b) with time of mango using backup in the evening. 63
Fig. 4.13. Variation of moisture content (w.b) with time of pineapple using backup heater in the day and evening. 64
Fig. 4.14. Variation of moisture content (w.b) with time of mango using backup heater in the day and evening. 65
Fig. 4.15. Variation of moisture content (w.b) with time of pineapple for the different tests carried out. 66
Fig. 4.16. Variation of moisture content (w.b) with time of mango for the different tests carried out. 66

CHAPTER ONE: INTRODUCTION

1.1. Background

Agriculture in Ghana is mainly carried out on a smallholder basis and it is mainly the traditional system of farming. About 90% of farm holdings are smaller than two hectares in size (MOFA, 2011). But there are some large farms and plantations, especially palm oil, rubber and coconut and to a lesser extent, maize, rice and pineapples. In Ghana, cocoa, oil palm, coconut, cola and rubber are considered as the major industrial crops while cassava, cocoyam, yam, maize, rice, millet, sorghum and plantain are the main starchy and cereal staples in the country. The main agricultural produce under the category of fruits and vegetables are citrus, pineapple, banana, pawpaw, cashew, mango, tomato, okro, egg plant, pepper, asian vegetables and onion (MOFA, 2011).

MOFA (2011) stated that although agriculture is the largest sector of the economy in Ghana, contributing about 39% of GDP, there are basic problems faced by this sector which include high post harvest losses as a result of poor postharvest management. For instance, Zakari (2012) has given an estimate showing that the average postharvest loss of mango is between 20 % and 50 %. The main reason for losses has been attributed to the fruit fly presence and a host of diseases as well as lack of cold chain facilities, and long transit time. Antwi (2007) also suggested that there would be loss of fresh produce during the harvest period because of excess production which could lead to unsold produce. This surplus produce should be stored so that it can be used later. But it might be unsafe to keep these produce over a long period due to high moisture content, physical damage, pathogens etc.

In order to reduce such postharvest losses to enable farmers increase the quality of their products, efficient and affordable drying methods are necessary. Locally manufactured low cost solar dryers provide a means of reducing postharvest losses (Weiss and Buchinger, 2002).

1.2. Problem Statement

More than 80% of most fruits is water (GEPC, 2005). Micro-organisms can obtain nutrients and water for their growth from the fruit in which they grow. Hence, the fruit must be dried in order to stop the multiplication of micro-organisms and store it for longer period.

Traditional open sun drying is a common and widely used method for drying of agricultural produce including fruits, vegetables and cash crops. It is the simplest way of drying foods by direct exposure of the product to the sun. Even though sun drying is the cheapest method, the quality of the dried product is far below standards. This method has some disadvantages including contamination, damage by birds or insects and slow or intermittent drying. Dried product quality improvement and reduction of losses can be achieved by the introduction of suitable drying technologies such as solar drying.

However, most solar dryers that are constructed use only solar energy as a heat source for drying. This makes the solar dryer to be dependent on climatic conditions limiting its use in cloudy periods and at night. As a result, agricultural produce that are harvested in the rainy season are still subjected to spoilage.

1.3. Justification

Fruits that can be dried in Ghana include pineapples, papaya, mango, banana and coconut. Dried fruit is mainly consumed as a snack and as an ingredient for breakfast cereals, healthy ready-to-eat snacks and desserts. Breakfast cereal mixtures and bakeries are one of the largest end users of dried fruit (GEPC, 2005).

In Ghana, the international market has been the target market for dried fruit products. Dried fruit is not yet popular in terms of both consumption and exportation. But as awareness is created locally, it is expected that demand will eventually grow and attract more operators in the sector (Zakari, 2012).

In recent years, the use of solar energy has become more popular. Solar radiation is the main source of energy for solar drying. The use of solar energy in the agricultural sector to preserve grains, fruits, and vegetables is feasible, economical and ideal for farmers in many developing countries (Mustayen et al., 2014). But for most crops harvested during the rainy season, preservation by using only solar energy proves difficult (Barki et al., 2012). Hence, an additional means of heat supply must be incorporated into solar drying.
This makes the dryer to operate continuously at night and in cloudy days.

1.4. Research Objectives

The main objective of the research was to design, construct and evaluate the performance of a solar dryer incorporating a charcoal stove which can be used as an additional heat source.

1.4.1. Specific Objectives

The specific objectives of the research were:

1. To design and construct a solar dryer with charcoal stove as a backup heat source.
2. To evaluate the performance of the dryer using different parameters such temperature, moisture content of the produce, drying period, drying rate and efficiency. 3. To compare the performance of the solar dryer with and without the backup

heater.

CHAPTER TWO: LITERATURE REVIEW

High moisture content in some agricultural produce after harvesting can facilitate the growth of microorganisms resulting in spoilage of the produce. Reducing moisture content of food to between 10 and 20% prevents bacteria, yeast, mold and enzymes from spoiling it (Scanlin, 1997). Drying is the oldest technique used for food preservation. It can reduce wastage of surplus production and also make produce lighter, smaller and easier to handle (Green and Schwarz, 2001).

Drying is defined as a process of moisture removal due to simultaneous heat and mass transfer (Ertekin and Yaldiz, 2004). Heat transfer must occur to change the temperature of the material to be dried and mass transfer occurs when moisture is removed from within the material to the surface accompanied by its evaporation from the surface to the surrounding atmosphere (Hii *et al*., 2012). For successful drying, enough heat to draw out moisture without cooking the food and adequate dry air circulation to carry off the released moisture should be applied. In addition, the moisture must be removed as quickly as possible at a temperature that does not seriously affect the flavor, texture and color of the food (Sanni *et al*., 2012).

Drying is a very suitable preservation technique for developing countries with poorly established low-temperature and thermal processing facility (Hii *et al*., 2012). Drying can ensure continuous food supply and production of high quality marketable products (Weiss and Buchinger, 2002).

2.1. Sun Drying

Brenndorfer *et al.* (1987) defines sun drying as the spreading of a produce to the sun on a flat surface. In sun drying, the product is heated directly by the sun's rays and moisture is removed by natural circulation of air. The process of sun drying does not require any other source of energy except sunlight which makes it the cheapest method (Hii *et al*., 2012).

Even though sun drying is the earliest and commonest method of drying agricultural produce, it is labor and time intensive and also requires a lot of space per unit throughput.

The product will absorb only a portion of the sun's energy while the remaining radiation is reflected. Additionally, wind blowing on the surface results in heat loss which can introduce moisture (Schiavone, 2011). During sun drying the agricultural product can be rewetted, especially at night when the ambient temperature is decreasing causing an increase in the humidity (Weiss and Buchinger, 2002).

Traditional open sun drying has many limitations. Intermittent and irregular loss of moisture and lower rate of drying increases the risk of spoilage during the process of drying. Due to high relative humidity and low air temperature, the final moisture content of the dried produce may be high enough to result in spoilage during storage (Brenndorfer *et al*., 1987). Sun drying can lead to quantity and quality losses of the dried product. The losses can be associated with contamination by dust, dirt and infestation by rodents, insects and animals (El-Sebaii and Shalaby, 2012).

2.2. Solar Drying

Solar drying is a viable option to open sun drying. Solar dryers can increase the drying temperature and reduce relative humidity resulting in lower moisture content of dried product. Unlike sun drying, a solar dryer constitute a specialized structure that controls the drying process and protects the produce from damage by dust, rain and insects (Raju *et al.*, 2013). Since the products are protected and the drying time is reduced significantly, the quality of dried product obtained by solar drying is better than that of sun drying (Seveda, 2013).

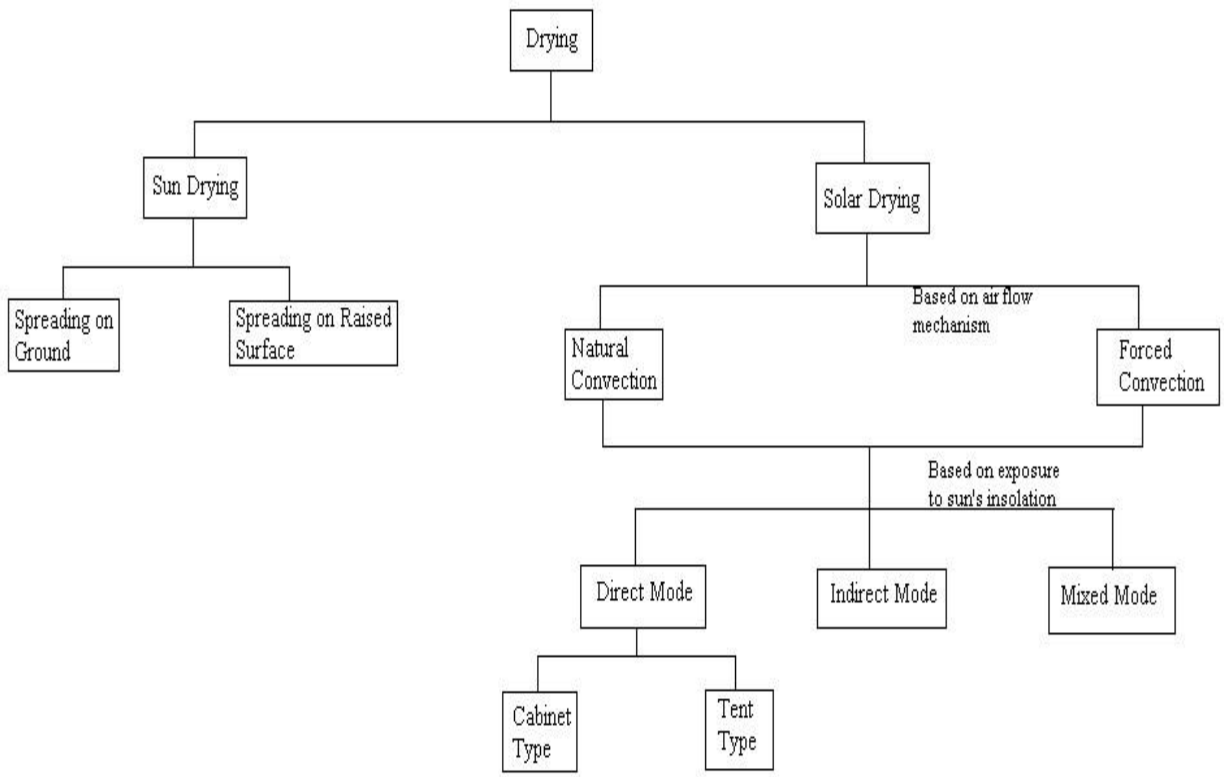

Fig. 2.1. Schematic Diagram of Sun and Solar Drying.

2.3. Types of Solar Dryers

There are different types of solar dryers and literature classifies them based on various criteria. Accordingly, solar dryers can be classified as direct or indirect based on whether the material to be dried is exposed to direct insolation or not. Based upon the mechanism of air flow through the dryer, solar dryers can be either natural convection solar dryers or forced convection solar dryers (Brenndorfer *et al.*, 1987). Natural convection solar drying also called passive solar-energy drying system utilizes the natural principle that hot air rises (Green and Schwarz, 2001). The flow of air through such dryers is based on thermally induced density gradient. On the other hand, forced convection dryers or active solar dryers force the flow of air through the drying chamber using a pressure difference generated by a fan (Brenndorfer *et al.*, 1987).

2.3.1. Direct Solar Dryers

In direct solar dryer a structure with transparent covers and side panels is used to keep the agricultural produce to be dried. Solar radiation absorbed by the product and the internal surfaces of the drying chamber generate heat thus increasing the temperature of the crop and its enclosure (El-Sebaii and Shalaby, 2012). These types of dryers are suitable for places where direct sunlight can be received for longer periods during the day (Mustayen *et al.*, 2014).

Brenndorfer *et al.* (1987) classifies direct solar dryers using natural convection with combined drying and collector chamber as cabinet dryer and tent dryer. Figure 1 shows sample of cabinet dryer. It can be made from wooden box insulated at its base and side.

The material to be dried is kept on a perforated tray. Air coming from the lower part of the cabinet flows through the holes and leave through the upper ventilation holes maintaining a natural air circulation (Mujumdar, 2006).

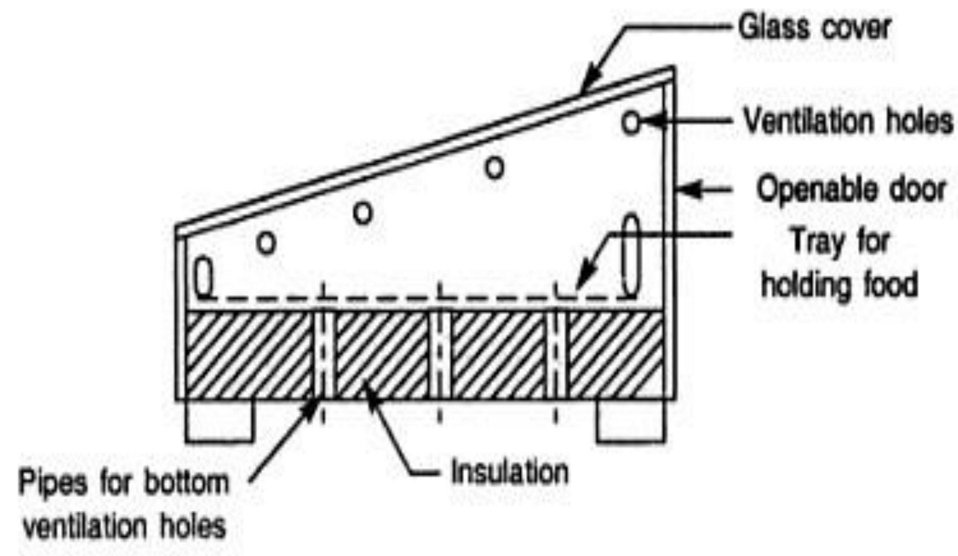

Fig. 2.2. Cabinet Dryer

Source: Hii *et al*., 2012

In order to avoid the effect of shading by the sides, the length of the cabinet dryer should be three times its width. The roof should also be slanted to avoid the accumulation of water during rainy periods. Portable cabinet dryers can be constructed from wood or metal whereas for fixed structures stone, brick, mud or concrete could be used. For maximum internal temperatures, the base and sides of the cabinet should be insulated with a layer of at least 50 mm thick sawdust, dried grass or leaves, coconut fiber, bagasse or wood shavings. Plastic mesh or netting can be used to construct the drying trays (Brenndorfer *et al*., 1987).

Tent dryers consist of a tent like framework that is usually covered with plastic sheet. Figure 2.3 shows a sample of a tent dryer. In this dryer, a white plastic sheet is used to cover the ends and the sides facing the sun while black plastic sheet is used to cover the side in the shade and on the ground within the tent. The drying tray is placed centrally along the length of the tent.

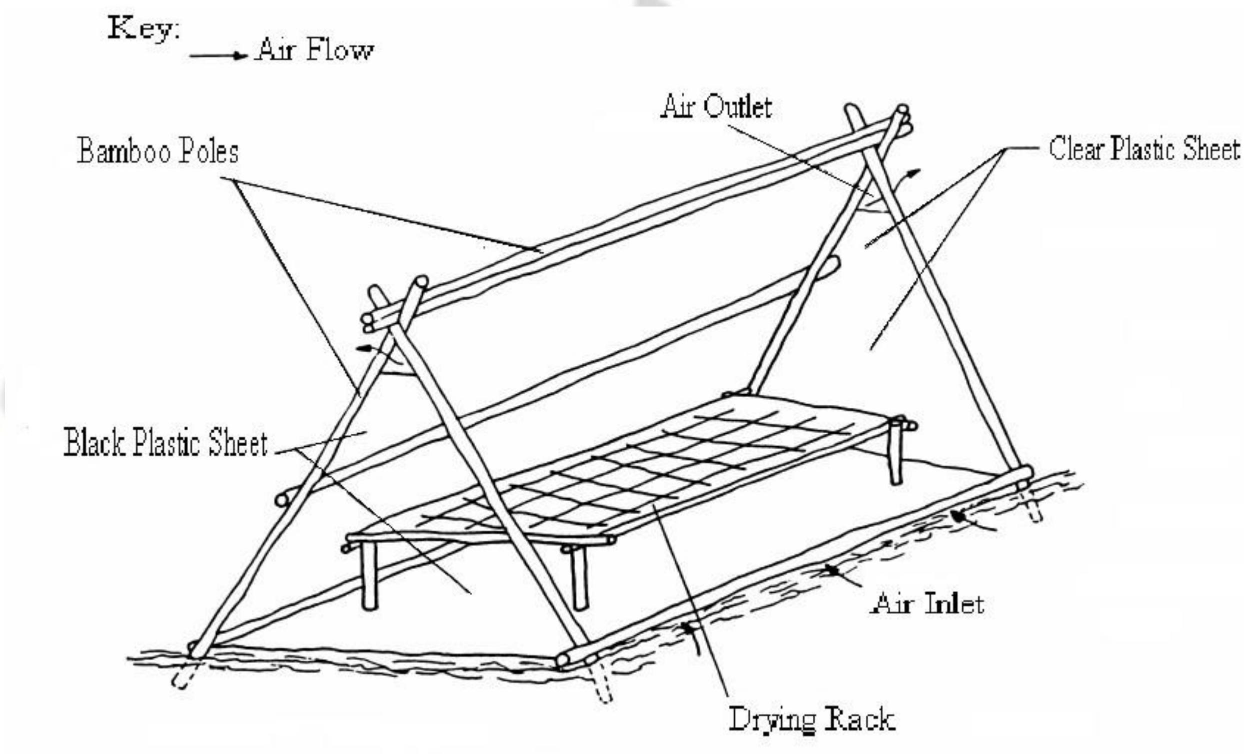

Fig. 2.3. Tent Dryer

Source: Brenndorfer *et al.*, 1987

Raju *et al.* (2013) designed and fabricated a direct solar dryer of cabinet type. It was used to dry a batch of 20 kg of fresh vegetables such as chilly and tomato in two days. The dryer was constructed in India and experimental drying tests were carried out with a prototype of the dryer having 1.03 m^2 of solar collector area. This dryer has a dimension of 100x103x76 cm^3 where the sides are constructed from galvanized steel and the bottom from wood. A glass is used as a cover and a hole of 5 cm was made for air circulation. Optimum temperature of the solar dryer was designed to be 60°C with ambient temperature or inlet air temperature of 30°C. At the end of the first day of drying 3000 grams of potato using this dryer, the weight of the produce was reduced to 1180 grams while when drying the same amount using open sun drying the weight reduced to 1550 grams. Final weight of the potato was reduced to 550 grams on the second day while using the dryer where as it was reduced to 920 grams when open drying.

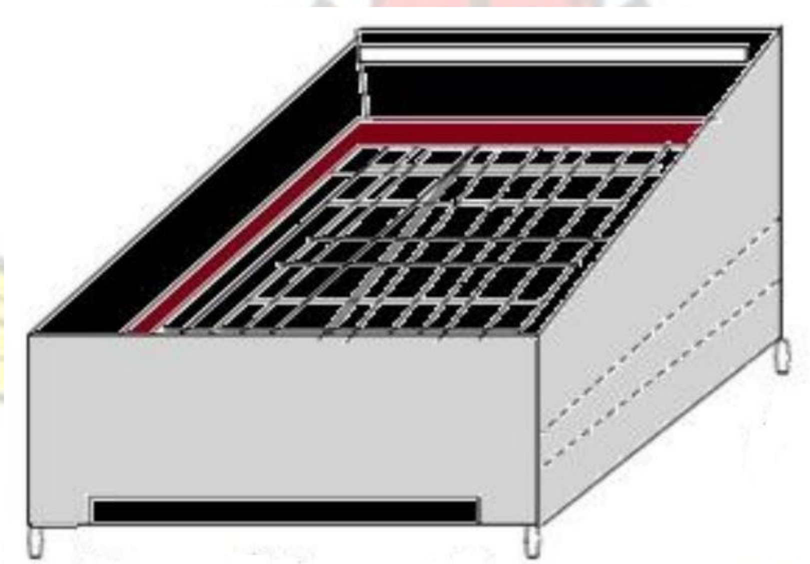

Fig. 2.4. Pictorial View of Cabinet Dryer

Source: Raju *et al.*, 2013

The design also included a mechanism of collecting the heat coming out of the dryer using copper tubes for water heating system. The authors did not mention the particular application of the heated water, but the advantage of including this system should be compared with the increase in cost it will incur so that it can be afforded by small farmers.

Medugu (2010) fabricated and studied the performance of a forced convection direct mode solar dryer. In addition to the basic components of a solar dryer, this design consisted of a chimney and a 40 W photovoltaic module used to power and run a dc fan. Drying 50 kg of tomato with an initial moisture content of 90% using this type of solar dryer was completed within 129 h which is about 55% of the time required to dry using natural sun drying. The author also evaluated the performance of the solar chimney dryer in comparison with solar cabinet dryer without a chimney which took about 138 h to dry the same quantities of tomato. Higher quality dried product in terms of its color and flavor was obtained when using the solar chimney drier.

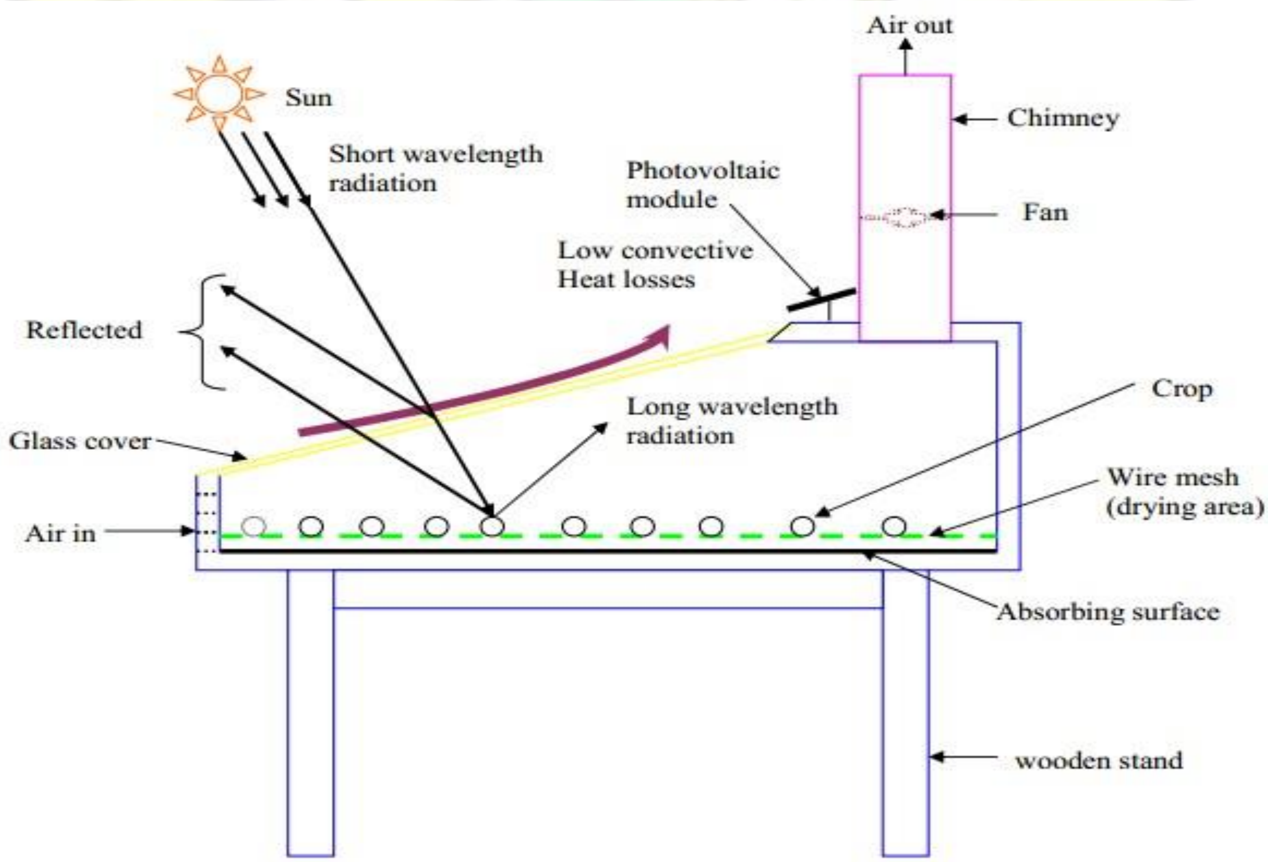

Fig. 2.5. Forced Convection Direct Mode Solar Dryer

Source: Medugu, 2010

A drying period of 129 h for drying tomato, which is about more than 5 days, is longer compared to drying period reported by other solar dryer designs. No justification was given for the long drying periods but it could be due to the fact that the experimental tests were carried out during the wet season, when most of the days were cloudy. The author indicated that the solar dryer was constructed from entirely quality materials which may increase the cost of the dryer. In addition, the presence of photovoltaic module as a power source to operate a dc fan makes the fabrication of the dryer costly.

2.3.2. Indirect Solar Dryers

In indirect solar dryers, a solar collector is used to heat the air entering the drying cabinet where the crops are placed. The heated air is made to pass through the drying bed for moisture removal by convective heat transfer between the wet crop and the hot air (Hii *et al*., 2012).

Svenneling (2012) designed and tested an indirect solar dryer for drying pineapples in Ghana. The solar collector has an area of 1.05 m^2 and the air duct has a gap of 0.2 m. A 1.2 m long chimney with a diameter of 0.1 m was made from metal sheet and is connected to the drying chamber. Laboratory drying test of pineapples showed that the slices had become case hardened when dried at 70^{o}C for five hours. But when dried at 50 ^{o}C, it took about 23.43 hours for the pineapple pieces to reach a moisture content of 10%. At this point, the pieces had become light yellow and pale and were ready to be eaten. The longer drying period in the laboratory was attributed to inadequate ventilation in the oven**.** When using the solar drier at the test location, the temperature in the collector and the drying chamber reached approximately 60 ^{o}C and 50 ^{o}C respectively. The moisture content was reduced from 90 % on wet basis to about 10 % within 16 sunshine hours. It was also shown that the drying rate was faster on the lower shelf that is closer to the collector than the upper shelf.

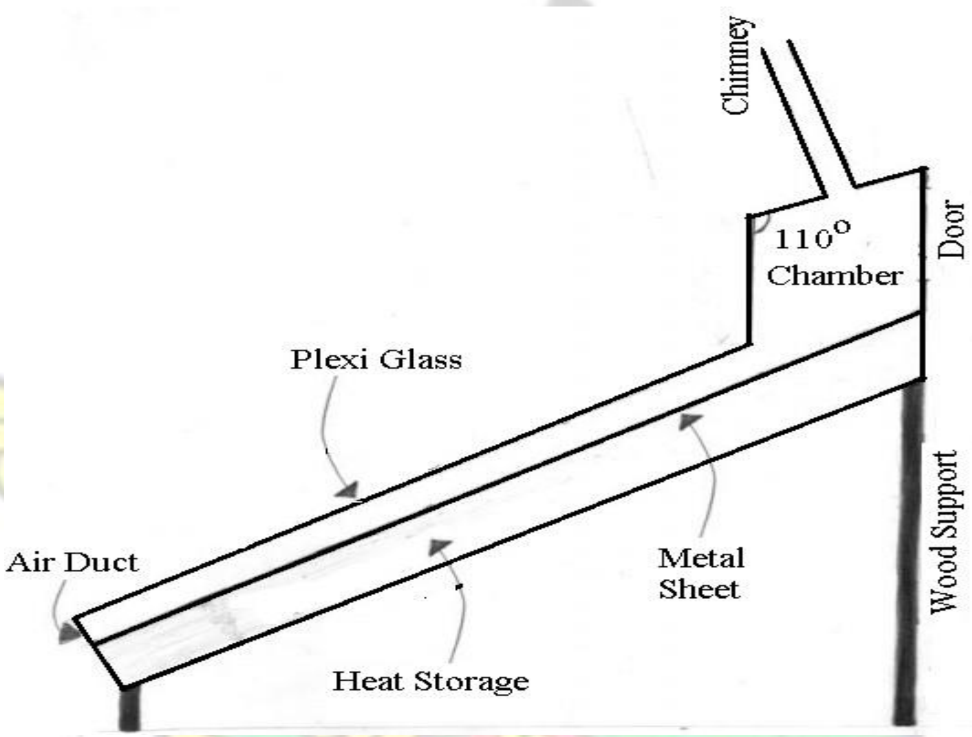

Fig. 2.6. Sketch of Indirect Solar Dryer

Source: Svenneling, 2012

It was indicated that, due to high humidity in Ghana, some of the tools used to construct the dryer started to corrode after only a short period of time which affected the modification of dryer. The large size of the dryer had also made it difficult for handling while moving it from one place to another.

Svenneling (2012) stated that it is unreliable to use the sun as the only source of energy.

Due to cloudy or rainy weather, tests that were supposed to be done were not completed. Even though drying in Ghana is possible during the dry season, it is difficult to preserve pineapples during the rainy season. A future work was also recommended on studying the weight gain during the night time because of the high humidity.

Alonge and Adeboye (2012) constructed an indirect mode passive solar dryer with easily available local materials such as wood, glass sheet, metal sheet, chicken net and mosquito net. They carried out tests under no-load and load conditions. During no load test the maximum temperature in the indirect solar dryer reached up to 48 ^{o}C while the ambient temperature was 39 ^{o}C. For the loaded condition, 180 g of pepper with 78.9 % of initial moisture content on a wet basis was considered. It took 51 hours to reduce the moisture content of the pepper to 24% (w.b). The drying rate of the produce in the indirect passive solar dryer was 2.55 g/h while it was 2.17 g/h in open sun drying.

Fig. 2.7. Indirect Solar Dryer

Source: Alonge and Adeboye, 2012

2.3.3. Mixed Mode Solar Dryers

Mixed mode solar dryers combine the basic characteristics of indirect and direct type solar dryers (Hii *et al*., 2012). Heat required for drying the produce is obtained by two ways, through pre-heated air coming from the solar collector and a direct solar insulation on the produce (El-Sebaii and Shalaby, 2012).

Basumatary *et al.* (2013) designed and constructed a low cost mixed type solar cabinet dryer. The drying chamber is made from wood where the inside is coated with metal and is covered with transparent plastic paper. The authors indicated that the drying trays can be made from non-corrosive stainless steel, but instead preferred to use bamboo nets for their lower cost. The solar collector is made from dark black painted non-corrosive galvanized iron (GI) sheet that is covered with transparent glass sheet or plastic paper.

During the experiment they carried out on a full sunny day, the average measured temperature on the upper tray was 63 ^{o}C while the ambient temperature was 31 ^{o}C. They have also designed another dryer by connecting three solar collectors with the drying chamber. In this case, the dryer temperature has increased by 2 ^{o}C than that of the dryer with only one collector.

Within 7 hours of continuous chili drying in a full sunny day, 48.72 % of moisture was removed from the upper tray and 33.03 % from the lower tray. Sun drying of the chili under the same climatic condition removed only about 15.38% of the moisture content.

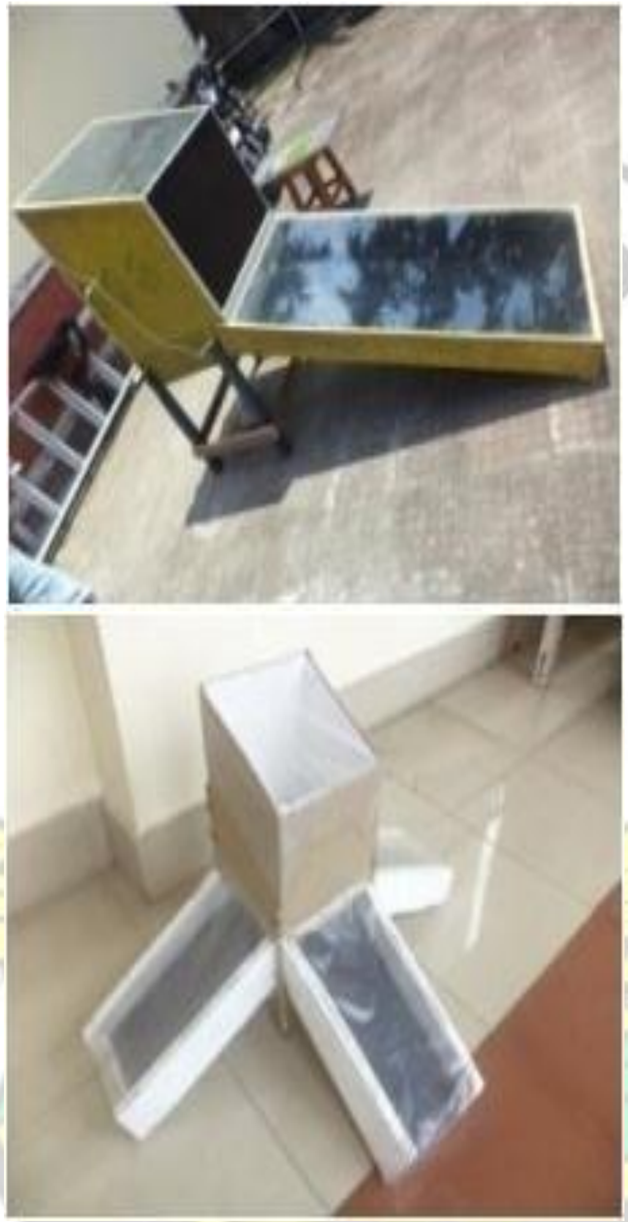

Fig. 2.8. Mixed Mode Solar Dryer

Source: Basumatary *et al.*, 2013

The mixed mode solar dryer constructed by Basumatary *et al.* (2013) was intended for drying low moisture content food products such as pepper, turmeric and cauliflower. This may limit the usage of the dryer by farmers producing high moisture content products such as fruits. In addition, the authors reported the performance of this dryer only for a full sunny day. Its evaluation on less sunny days or cloudy days was not included.

Forson *et al.* (2007)designed and reported a mixed mode natural convection solar dryer where the test location for their experiment was Kumasi, Ghana. They identified three main components of the dryer as an air-heater (primary collector), a drying chamber and a chimney. The top cover and sidewalls of the drying chamber are made to be transparent so that they serve as a secondary collector.

The dryer was used to dry cassava and the drying efficiency was estimated to be 12.3% with a drying time of 35.5 hour. With 162 kg of test load, 28.2 ^{o}C mean ambient temperature and initial moisture content of 66%, the final moisture content of the dried product was measured to be 17.3% while the temperature of the heated air in the air heater rose by about 10.9 ^{o}C.

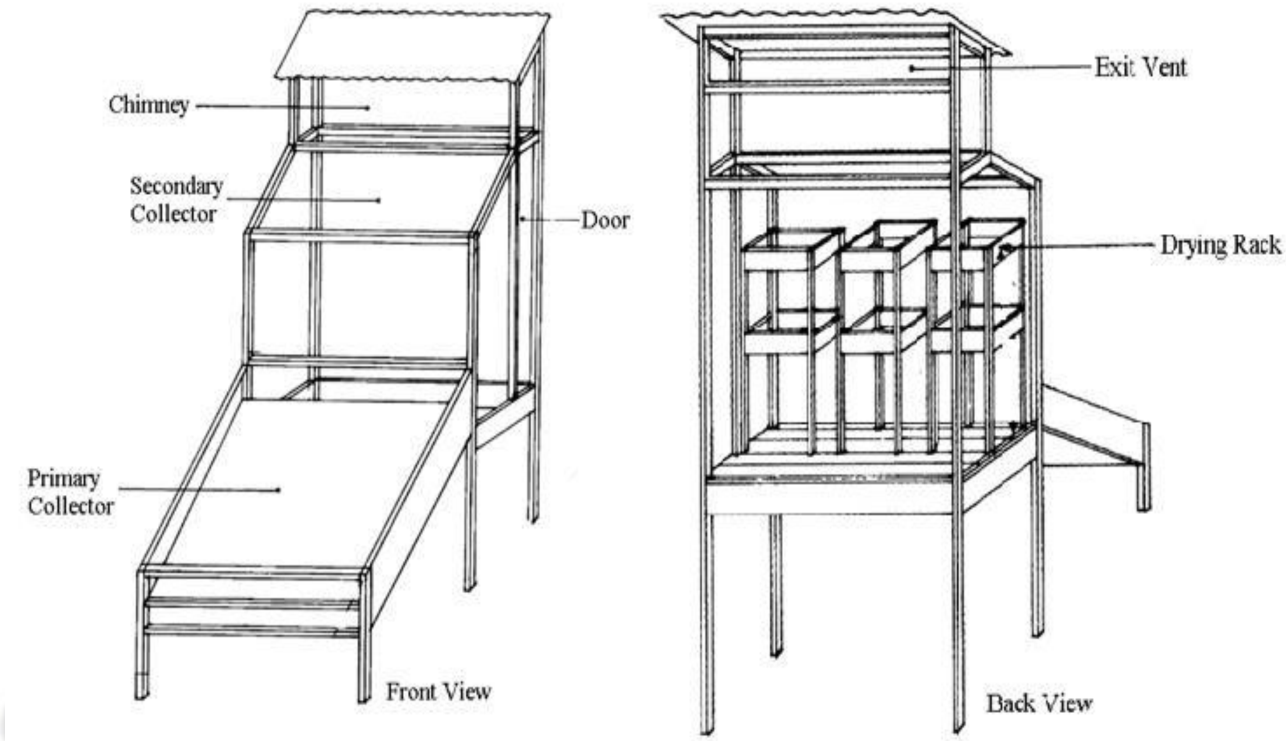

Fig. 2.9. Mixed Mode Solar Dryer

Source: Forson *et al.*, 2007

The research report of Forson *et al.* (2007) gave a detailed procedure on how to design a solar dryer. Basic design concepts and rules of thumb were also outlined in the paper. Accordingly, their design of solar dryer required 42.4 m^2 of solar collector for the expected drying efficiency.

2.4. Hybrid Solar Dryers

In addition to using only solar energy, hybrid systems incorporate another means of heating the air for drying a produce (Brenndorfer *et al.*, 1987). This enables the dryer to be operated during cloudy periods as well as at night.

A solar-biomass hybrid cabinet dryer was constructed in Philippines. The dryer uses a solar collector for heating the drying air during daytime operation whereas a biomass stove is used for operations during night time and cloudy conditions. Slanted at 15^o to the horizontal, the solar collector has an area of 2.12x0.9 m and is connected to the rear side of the drying chamber. The collector air gap is 0.05m.The drying chamber consisted of 30 aluminum wire net trays for holding the products. An exhaust fan, in which power is supplied by a 45 W electric motor, was fixed in the chimney to force ambient air to pass through the collector. The drying air temperature can reach up to 60 ^oC with 0.05 m^3/h airflow rate. The biomass stove uses coconut shell or charcoal as fuel input and the fuel consumption is about 2.0 kg/h. Moisture content of sliced pineapple was reduced from 85% to 20% wet basis in about 18 hours (IAE/UPLB, 2002).

Fig. 2.10. Solar-Biomass Hybrid Cabinet Dryer

Source: IAE/UPLB, 2002

In this hybrid solar-biomass dryer the fan is run by an electric motor. This limits its use in rural areas where there is no electric supply. In addition, the total cost of the drying system (including the solar collector and gasifier stove), which is estimated to be about US$ 1,120 (as of February 2002), is very expensive to be afforded by most farmers in developing countries.

Performance of a solar dryer with backup incinerator was evaluated by Barki *et al.* (2012) in Makurdi, Nigeria. The three main components of the hybrid solar dryer were flat plate collector, drying chamber and incinerator. The solar collector, made from a thick clear glass supported by a wooden casing, has an area of 0.82 m^2 and the absorber plate has a depth of 0.14m. An incinerator of dimensions 49 cm x 124 cm x 40 cm is connected to the drying chamber that can be used as an additional heat supplying source. Charcoal is the biomass that was burnt in the incinerator and water, which was allowed to flow by gravity, was used to convey the heat.

On load test was carried out using grated cassava with initial moisture content of 69.8%. It took 12 h to reduce the moisture content to 47.19 % using only the solar dryer where as the combined solar-incinerator dryer took 16 h to dehydrate the grated cassava sample to moisture content of 47.48%. The incinerator dryer and open sun drying (control) both took 20 h to reach 47.99% and 47.01% of moisture content, respectively.

Barki *et al.* (2012) used the open sun drying as a control for evaluating the performance of the solar and solar-incinerator dryers. This implies that the comparison between the solar dryer with that of the combined solar-incinerator dryer was based on tests that were carried out at different times. The ambient temperature and humidity when testing the solar dryer alone and when testing the solar-incinerator dryer would be different, it might be more sunny or cloudy. A better comparison could have been made if an additional similar design was constructed which would have made it possible to run tests simultaneously.

2.5. Solar Dryers with Concentrators

In solar drying, concentrating type of collectors can be used in order to increase the intensity of radiation on the absorbing plate (Brenndorfer *et al.*, 1987). This increases the efficiency of the solar dryer during cloudy and hazy conditions.

Ringeisen *et al.* (2014) evaluated the effectiveness of a direct type solar dryer with a concave solar concentrator. The concentrator was made from materials that are readily obtainable in developing countries with lifetime expectancy of at least three years. It was made to be modular so that it can be adapted for dryers of various sizes. The solar dryer is constructed from lightweight wooden frame that is wrapped up with thick plastic sheet. A corrugated piece of black painted aluminum was placed on the floor of the dryer to be used for absorbing solar radiation. A concave solar concentrator made from polished aluminum sheet was fixed on a wooden L-shaped frame. Tests were carried out using 5 mm thick sliced tomatoes with initial moisture content between 92.2 and 94.4%. On a fully sunny day, the reduction in the drying time was about 1.54 h for the tomatoes to reach moisture content of 10%. This was 22.3% faster than that of the solar dryer without concentrator. It is also shown that the concentrators can effectively reduce the drying time during unfavorable ambient temperature and relative humidity conditions.

Fig. 2.11. Solar crop dryer and concave solar concentrator

Source: Ringeisen *et al.*, 2014

Similarly, Stiling *et al.* (2012) compared the performance of two mixed-mode solar dryers. The two dryers were identical except that one of the dryers consisted of easily adjustable and mobile flat solar concentrating panel. The concentrating panels in this study are separate from the dryer and hence can be adjusted to different orientations depending on the position of the sun. This helps to increase the amount of solar insulation striking the collector. Aluminized Mylar sheet stapled on a wooden frame is used as the reflective material. Parameters such as solar radiation, humidity, temperature, air speed and weight loss of the produce to be dried were used to evaluate the performance of the solar dryers. The result of the study reveals that mixed-mode solar dryer with concentrating solar panels increases the temperature and lowers the relative humidity of the dryer. This reduced the drying time in the solar dryer with the concentrated solar panel by 27.0%.

Fig. 2.12. Solar dryer with two solar concentrating panels

Source: Stiling *et al.*, 2012

For solar dryers with concentrators, average values of ambient and drier temperatures were calculated from graphs provided in the papers. But other parameters such as drying rate and drying time were not directly given, except for the comparison between the solar dryers with the concentrated solar panels and the dryer without the panels.

2.6. Materials Used for Constructing Solar Dryers

As described in the previous topic on different types of solar dryers, different designs used different material for constructing the driers. Most of the designs used the availability of the materials as a major criterion. Other criteria for choosing the materials were indicated as cost, quality and ability to withstand harsh environmental conditions such as very hot weather and rain. The summary of the materials used in the review are given in Table 2.1.

Table 2.1. Material Usage

Component		Material	Usage, %
Collector	Transparent	Glass	50
		Plexiglas	20
		Plastic	20
		Polycarbonate	10
	Absorber	Galvanized steel sheet	25
		Aluminum sheet	25
		Granite stone	12.5
		Galvanized iron sheet	25
		Polyethylene film	12.5

Drying Chamber	Structure	Wood	80
		Metal	20
	Cover	Glass	70
		Plastic	30
Tray	Net	Chicken wire	20
		Stainless steel	40
		Bamboo net	10
		Aluminum wire net	20
		Plastic screen	10
	Frame	Wood	50
		Angle bar	12.5
		No frame	37.5
Chimney		Plastic	25
		Metal sheet	50
		PVC pipe	25
Air Vent Cover		Mosquito net	20
		Aluminum mesh	10
		No cover	70

In addition to the materials used above, some dryers included glass wool, compacted glue, thermocol sheet, foam band and sawdust for insulating the dryer and concrete stone was used as a heat storage mechanism.

Table 2.2. Summary of the review of different types of dryers.

Dryer	Efficiency, %		Drying Time	Collector Area, m^2	Temperature, °C		Moisture Content (MC), %		Drying Rate, g of H_2O removed/hr	Cost**	Cited Literature
	Collector Efficiency	Drying Efficiency			Ambient	Dryer	Initial MC	Final MC			
Direct	30	NA*	2 days	1.03	30	60	89.6	13	7.862	NA	Raju*et al.*, (2013)
	NA	NA	129 h	NA	NA	NA	90	58	NA	Relatively Inexpensive	Medugu (2010)
Indirect	NA	NA	16 sunshine hours	NA	30	50	87	10	2.5	NA	Svenneling (2012)
	NA	NA	51 h	NA	39	48	78.9	24	2.55	Low	Alonge and Adeboye (2012)
Mixed Mode	NA	NA	7 h	0.94	31	63	82	20	28	Rs. 1280/4000	Basumatary*et al.*, (2013)
	NA	12.3	35.5 h	42.4	28.2	39.1	66	17.3	2.82	NA	Forson*et al.* (2007)
Hybrid	NA	NA	18 h	1.91	NA	60	85	20	NA	US$ 1120	UPSL/UPD and IAE/UPLB, 2002
	17	13	16 h	0.82	40	50	69.8	47.48	0.966	NA	Barki*et al.* (2012)
Dryers with Concentrators	NA	NA	NA	0.64	NA	NA	92.2-94.4	10	NA	< US$50	Ringeisen*et al.* (2014)
	NA	NA	NA	22.5	30.5	65.5	90	< 20	NA	NA	Stilling *et al.* (2012)

Note: * - Not Available

** - cost of the dryer displayed here are as per the authors report in the articles.

As shown in Table 2.2, almost all papers have reported the numerical values for initial and final moisture content of the produce to be dried, ambient and dryer temperature and collector area. These parameters are useful as they form the basis for designing the dryer size and capacity. The efficiency of the solar dryer which includes the collector efficiency and the drying efficiency was not reported by most literatures covered in this review. In addition, only a few literature reported the numerical values for the cost of the drier, while some gave the relative cost using qualitative terms.

Although different reports provided different results which were obtained from various tests, numerically comparing these values would be difficult because of the differences in design, produce to be dried and ambient conditions.

2.7. Gaps Identified in the Review

Some of the gaps identified from the review of the different types of solar dryers are summarized in Table 2.3. Identifying these gaps would help to choose which type of dryer is more suitable for study. These gaps are mainly related to poor performance of the dryer during the wet season, method of performance evaluation, type of material to use for construction, cost, etc.

Table 2.3. Summary of Gaps Identified in the Review

Dryer	Gaps
Direct	Longer drying period when used during wet season
Indirect	• Corrosion of tools used to construct the drier affecting its modification • Incomplete test due to cloudy or rainy weather • Difficulty in handling and moving the dryer due to large size
Mixed Mode	Drier performance was reported under test carried out during a full sunny day, no evaluation report done under less sunny days or cloudy days
Hybrid	• Higher cost of construction • Tests done for comparing the solar drier alone with that of the hybrid solar-incinerator drier were not carried out simultaneously
Solar Dryers with Concentrators	Some important parameters were not directly given in the report

Direct solar dryers are commonly used in areas where direct sunlight is received for longer periods during the day (Mustayen *et al.*, 2014). They are much simpler and easier to construct than any other types of solar dryers. However, direct solar dryers have some limitations. Having small crop handling capacity, overheating or discoloring of the produce due to direct exposure to sunlight and so reduction in quality are some of them. The transmissivity of the glass cover is also reduced due to the condensation of evaporated moisture on the cover (El-Sebaii and Shalaby, 2012).

Indirect solar dryers, on the other hand, can overcome the drawbacks of direct solar dryers. In rural areas, locally constructed indirect natural convection solar dryer is suitable for drying fruits and vegetables (Mustayen *et al.*, 2014).

In addition, Gregoire (1984) stated that using indirect dryers can reduce vitamin loss, especially vitamin C. This is due to the fact that some foods may become discolored or may lose much of their nutritional value if exposed to direct rays of the sun.

Considering the drawbacks of direct solar dryers and planning to use the dryer to be constructed to dry fruits, an indirect type of solar dryer will be designed and constructed. In addition, in order not to be dependent solely on the sun, a backup heater system is included.

2.8. Components of Solar Dryers

Solar dryers are mainly made up of three parts. These are solar collector, drying chamber and chimney. These parts are briefly discussed below.

2.8.1. Solar Collector

Solar collectors are used to convert direct and diffuse radiation from the sun into thermal energy (Jercan, 2006). It is a special kind of heat exchanger that transforms solar energy to heat. Energy is transferred from a distant source of radiant energy to a fluid (Duffie and Beckman, 1980).

For applications requiring less than 80 ^{o}C, flat plate collectors are widely used (Struckmann, 2008). Flat plate collectors are mechanically simpler and require little maintenance than concentrating type of collectors (Duffie and Beckman, 1980).

Generally, flat plate collector designs consist of three major parts. These are transparent cover, absorber plate and insulation.

The transparent cover also called glazing is where the solar energy passes through the collector (Saxena and Goel, 2013).Using a transparent cover reduces heat loss and helps to obtain higher temperature. Glass is the common transparent cover for collectors, but some plastics have also desirable characteristics. Although plastics can transmit as much solar radiation as glass and resist impact stress better than glass, it allows more thermal energy loss than glass (Spillman, 1980).

Absorber plate is made from a material which can rapidly absorb heat from the sun's rays. It is usually made from black painted metal sheet (Amrutkar *et al.*, 2012). Insulation should be used at the back side of the absorber to minimize heat loss. The material chosen as insulator should be stable at high temperatures, i.e. it should not break down at high temperatures. In order to reduce heat loss from the sides of the collector, it should be incorporated into a box. Collector boxes should be strong enough to resist loads imposed by wind and need to be sealed to exclude water (Spillman, 1980).

2.8.2. Drying Chamber

The drying chamber will be an enclosed structure where drying takes place. It will consist of trays for putting in the produce to be dried. At the drying chamber there should be means for loading and removing the material to be dried. This is usually provided by a door at the back side of the dryer. The drying chamber should be insulated and well sealed in order to contain the heated air without any leaks.

2.8.3. Chimney

All solar dryers should have a means to let out the exhaust air. Most solar dryers have a chimney to let out the hot air that picked up moisture from the produce kept in the dryer to be dried. When the air inside the chimney has a temperature greater than the ambient air such that the density of air outside the chimney is greater than inside, there would be a flow through the chimney (Ekechukwu and Norton, 1995).

2.9. Performance Evaluation of Dryers

2.9.1. Collector Efficiency

Collector efficiency measures the thermal performance, i.e. the useful energy gain of the collector. Not all of the solar radiation from the sun incident on the collector surface is converted to heat. Part of the radiation is reflected back to the sky and the other component is absorbed by the glazing. Once the collector absorbs heat and as a result temperature gets higher than the surrounding, there will also be a heat loss to the atmosphere by convection and radiation (Struckmann, 2008).

$$\text{Collector Efficiency, } \eta_c = \frac{\upsilon \varrho \Delta T C_p}{I_c A_c} * 100 \quad \ldots\ldots (2.1)$$

where: υ – volumetric flow rate of air, m^3/s

ϱ – air density, kg/m^3

T – air temperature elevation, ^oC

C_p – air specific capacity, J/kg^oC

I_c – insolation on collector surface, W/m^2

A_c – collector area, m^2

2.9.2. Drying Efficiency

Drying efficiency is the ratio of the energy needed to evaporate moisture from the material to the heat supplied to the dryer. This term is used to measure the overall effectiveness of a drying system (Dhanushkodi *et al.*, 2014). But it may not be used for comparing one dryer with another due to different factors such as the particular material being dried, the air temperature and mode of air flow may differ for various dryers (Brenndorfe *et al.*, 1987).

$$\text{Drying Efficiency, } \eta_d = \frac{M_w L}{I_c A_c t} * 100 \text{ …… (2.2)}$$

M_w – weight of moisture evaporated, kg

L – Latent heat of evaporation of water (at temperature of dryer), kJ/kg

t – drying time

For a dryer assisted with a biomass heater,

$$\eta_d = \frac{M_w L}{I_c A_c t + (M_c * CV)} * 100 \text{ ……..(2.3)}$$

M_c – mass of biomass used

CV – calorific value of biomass

2.9.3. Drying Rate

Drying rate is the amount of evaporated moisture over time (Dhanushkodi *et al.*, 2014).

$$DR = \frac{M_i - M_d}{t} \text{ …… (2.4)}$$

M_i = mass of sample before drying

M_d = mass of sample after drying

t = drying period

2.9.4. Moisture Content

Moisture content is one of the important parameters that is taken to evaluate the performance of a dryer. Moisture content of a material can be given either on the basis of total weight of the material to be dried or the amount of solid weight present in the material. The moisture content on wet basis is given by the following equation (Fudholi *et al.*, 2011):

$$MC(w.b), \% = \frac{w-d}{w} * 100 \quad \text{……..(2.5)}$$

w = weight of wet material

d = weight of dry material

Dry basis moisture content is given by (Mercer, 2007):

$$\text{MC (d.b.) g water / g dry solids} = \frac{w-d}{d} \quad \text{…….. (2.6)}$$

Nocturnal moisture re-absorption or loss, Rn, is the ratio of the increase in moisture content during the night period to the moisture content value at the sunset of the previous day. If the value of Rn is positive, it indicates moisture re-absorption, but negative value implies further moisture loss (Medugu, 2010).

$$R_n = \frac{M_{sr} - M_{ss}}{M_{ss}} * 100 \quad \text{…….. (2.7)}$$

M_{sr} = moisture content at sunrise (%)

M_{ss} = moisture content at sunset (%)

CHAPTER THREE: MATERIALS AND METHODS

An indirect type solar dryer was constructed having three major components; a solar flat plate collector, a drying chamber and a chimney. The dryer mainly used the sun as a source of energy. But a stove with charcoal as feedstock of energy was incorporated to make the drying process continuous during the night time as well as cloudy and rainy periods.

3.1. Design Procedure

The design of the solar dryer took into consideration different design criteria and parameters. Some of these design criteria and parameters were from literature review while others were determined using a series of mathematical calculations. These design parameters included environmental conditions of the test location, drying temperature, amount of moisture to be removed, heat energy requirement and determination of airflow requirement.

The performance of the dryer was evaluated in Kumasi (Latitude 6^{o}42'N and longitude 1^{o}57'W) (Moujaled, 2014). According to measurements done by Meteorological Services Department of Ghana and Kwame Nkrumah University of Science and Technology, the average solar irradiation for Kumasi was about 340.8 W/m^2. The ambient temperature, T_a, for the test location was 25^{o}C (Forson et al., 2007 and Antwi, 2007) with relative humidity of 70 % (Antwi, 2007).

3.1.1. Drying Temperature

Scanlin (1997) recommended drying temperatures for fruits and vegetables to be between 37.7-54.4^{o}C. Higher temperature may cause sugar caramelization (browning of sugar) of many fruit products when drying. Hence, for designing the dryer, average drying temperature, T_d, of 45^{o}C was considered.

3.1.2. Amount of Moisture to be Removed

The formula to calculate the total amount of moisture to be removed (M_w) is given by Bassey and Schmidt (1987) as:

$$M_w = \frac{W_w\ (M_i - M_f)}{1 - M_f} \quad \text{............ (3.1)}$$

where: M_w = amount of moisture removed

W_w = initial total weight;

M_i = initial moisture content on wet basis;

M_f = the final moisture content on wet basis;

The quantity to be dried determines the drying space, and in this case since the dryer has three trays and was for experimental purpose, an initial amount of 3 kg was to be considered for designing the dryer. Hence, pineapple would be dried in a batch from its initial moisture content of 87% on wet basis (obtained using oven drying) to a final moisture content of 15% (FAO, 1997). Using equation 3.1,

$$M_w = \frac{3\ \text{kg} * (0.87 - 0.15)}{1 - 0.15} = 2.54\ kg$$

3.1.3. Heat Energy Required to Remove Water

The heat required to remove water from a produce was calculated using the formula provided by Mercer (2007). It considers drying as a two stage process where the first one is raising the temperature of the wet material to a desired level at which the moisture will be removed. This is given by:

$$Q_1 = W_w * C_p * T \quad \text{............... (3.2)}$$

where: C_p is the specific heat capacity of the produce (in kJ/kg ^oC) and

$T = T_d - T_a$, is temperature change (in ^oC).

Specific heat capacity of a food material can be determined using the following equation:

$$C_p = 1.424\ m_c + 1.549\ m_p + 1.675\ m_f + 0.837\ m_a + 4.187\ m_w + 2.0505\ m_i \ldots\ (3.3)$$

where: m_c = mass fraction of carbohydrate

m_p = mass fraction of protein

m_f = mass fraction of fat

m_a = mass fraction of ash m_w =

mass fraction of water m_i =

mass fraction of ice

Chaiwanichsiri *et al.*(1993) gave the chemical composition of fresh pineapples (Appendix 7). Using these values in equation 3.3 gives C_p = 3.81 kJ/kg^oC. Hence,

$$Q_1 = 3\ kg * 3.81\ kJ/kg^oC * (45 – 25)^oC = 228.6\ kJ$$

The second stage is evaporating the moisture from the produce. As water starts to evaporate after the produce is warmed up to the drying temperature, heat required to evaporate it is given by:

$$Q_2 = M_w * L \ldots\ (3.4)$$

$L = h_g - h_f$,, is latent heat of vaporization. The values for h_g (enthalpy of water as a vapor) and h_f (enthalpy of water as a liquid) at the drying temperature are obtained from steam tables.

h_g = 2583 kJ/kg

h_f = 188 kJ/kg

Q_2 = 2.54 kg * (2583 – 188) kJ/kg = 6083.3 kJ

Therefore, the total heat requirement = $Q_1 + Q_2$ = 228.6 kJ + 6083.3 kJ = 6,311.9 kJ. This value obtained is the theoretical value. It does not take into account the heat lost through the walls of the dryer or the heat leaving the dryer through the chimney.

3.1.4. Sizing the Collector

The daily average insolation of Kumasi is taken to be 15.48 MJ/m^2/day (ATPS, 2013). Struckmann (2008) gives a typical flat-plate collector efficiency (at ambient temperature of 25 ^{o}C and I = 400 W/m^2) to be between 25% and 45%. The collector efficiency is influenced by factors such as temperature, air flow rate, insolation, type of transparent material, absorber plate and insulation used (Struckmann, 2008). To achieve an optimal design, average value of collector efficiency of 35% was considered as a design parameter. As a result,

Daily expected energy production by the collector = 15.48 MJ/m^2/day * 0.35

= 5.42 MJ/m^2/day

For 2 days (the drying period), the energy production would be

= 2 * 5.42 = 10.84 MJ/m^2

Since the total heat energy required for drying is 6.31 MJ,

$$\text{Collector Area} = \frac{6.31\text{ MJ}}{10.84\text{ MJ/m}^2} = 0.58\text{ m}_2 \quad \ldots\ldots\ldots\ldots (3.4)$$

Hence, the area of the collector was approximated to 0.6 m^2. Forson *et al.* (2007) suggested the length-to-width ratio of a solar collector to be 1 – 2. Considering the ratio to be 2 for this design, the length and width of the collector was 1.1 m and 0.6 m, respectively. Here, it should be noted that the calculations done are approximated to fractions that are suitable during construction.

3.1.5. Collector Orientation and Tilt Angle

The flat plate solar collector should be tilted and oriented in a way that it receives maximum radiation. The collector performs well when it is oriented perpendicular to the sun. Optimal tilt angle varies according to the season. As a general rule, optimum angle of tilt is equal to the degree of latitude of the site (Weiss and Buchinger, 2002). For this design since the test location is Kumasi (Latitude $6^{o}42'$N and longitude $1^{o}57'$W) (Moujaled, 2014), a collector tilt angle of 10^{o} was considered. This was to help avoid the accumulation of rain water on the collector during rainy periods.

3.1.6. Air Flow Requirement

Scanlin (1997) recommends the range for air velocity to be between 0.51 m/s to 5.08 m/s. In addition, the depth of the air channel should be 1/15 to 1/20 of the length of collector. Taking the average factor of the depth of the air channel (0.058) as suggested by Scanlin (1997) and multiplying it with the height of the collector length gives the air channel depth.

$$\text{Depth of air channel} = 0.058 * 1.1 \text{ m}$$

$$= 0.0638 \text{ m} = 6.38 \text{ cm}$$

Also, Irtwange and Adebayo (2009) suggested that the optimum air gap between the absorber and the transparent cover should be between 4 cm and 8 cm. The calculated air gap of 6.38 cm falls within this range.

Hence,

Vent Area = width of collector * air gap

$= 60\ cm * 6.38\ cm = 382.8\ cm^2 = 0.03828\ m^2$

For an air velocity of 0.51 m/s,

Volume flow rate = Vent Area * Air Velocity ……….. (3.5)

$= 0.03828\ m^2 * 0.51\ m/s = 0.0195\ m^3/s$

Mass flow rate was determined by multiplying the volume flow rate by the density of air, 1.2 kg/m^3, yielding 0.0234 kg/s. This mass flow rate value lies between the range of 0.02 – 0.9 kg/s, as recommended by Forson *et al*. (2007) for natural convection dryers.

3.2. Construction of the Solar Dryer

3.2.1. Collector

The size of the collector was 1115 x 630 mm. It had three major components: transparent cover, absorber plate and insulation. The transparent cover is made from a single layer glass of 5 mm thickness. Aluminum sheet of 2 mm thickness, painted black, was used as an absorber. In order to minimize heat loss from the absorber plate, fiber glass insulation with thickness of 3 mm was placed underneath. The collector casing was made from wood and plywood. The air inlet opening was covered with mosquito net and a sliding door was attached to control the air flow into the dryer.

3.2.2. Drying Chamber

The drying chamber was made from plywood with wood support. It consisted of three trays, each with size of 60 x 50 mm, for the produce to be dried. The trays were made from perforated stainless steel. Stainless steel was chosen to avoid rusting due to high initial moisture content of the produce. At one side of the chamber, a circular hole of 10 mm diameter was made. This hole was used to pass hot air through the chamber when the charcoal stove was used for drying. A sliding door was used to cover this hole during the times when the stove was not connected. At the back of the drying chamber, a door will provide a means for loading and removing the material to be dried.

3.2.3. Chimney

The recommended height of the chimney is between 2 and 6 m for corresponding pressure across the dryer between 0.8 and 2.5 Pa (Forson*et al.*, 2007). Taking this into consideration, 2 m height of chimney was constructed. The material selected for constructing the chimney was galvanized metal sheet. The metal was rolled and welded to a diameter 15 mm. A cup at the top was used to cover the chimney to prevent rain from entering the dryer. The chimney was painted black to facilitate the flow of air through the dryer. This would allow increasing the temperature of the air flowing through it, i.e. the moist air coming from the drying chamber air outlet.

3.2.4. Backup Heater

The backup heater used charcoal as a source of energy. A “Gyapa” stove was used to burn the charcoal. “Gyapa” stoves are improved coal-pot in which the combustion chamber is heavily insulated with a ceramic liner.

For this project, the medium type of stove was used. It had a height of 25 cm and diameter of 31 cm. The heat from the stove used for drying was collected indirectly. This was to help avoid the contamination of the dried material from the smoke and flue produced when burning the charcoal.

The heat obtained by burning charcoal heated a circular tube of metal. One side of this metal tube was directly connected to the drying chamber. The metal tube was welded at the centre of a cylindrical cover which was used to trap the heat from the stove. This cover was well insulated using 2 cm of glass wool. The smoke from the stove escaped through a chimney which was connected at the top of the cover. At the top of the chimney was a flat surface metal sheet cover. Once the smoke from the charcoal had flown out, the chimney would be covered in order to prevent escaping of heat.

3.2.5. Drawing of the Dryer

The dryer was designed using a software called Siemens NX. The drawing of the design and the corresponding side views with dimensions are shown in Figure 3.1 and Figure 3.2. Figure 3.3 also shows the pictorial view of the dryer.

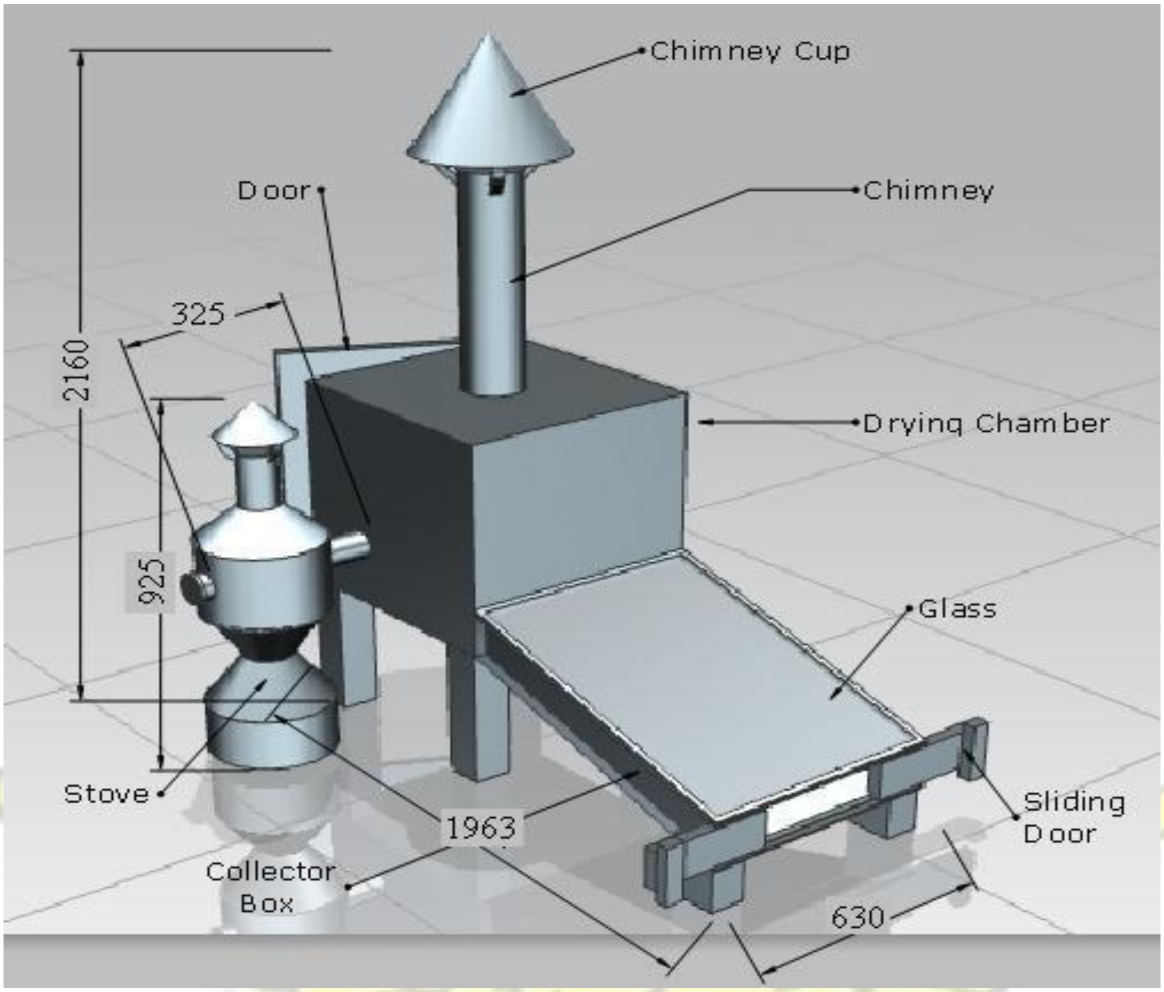

Fig. 3.1. Dryer drawing*

* All dimensions are in mm.

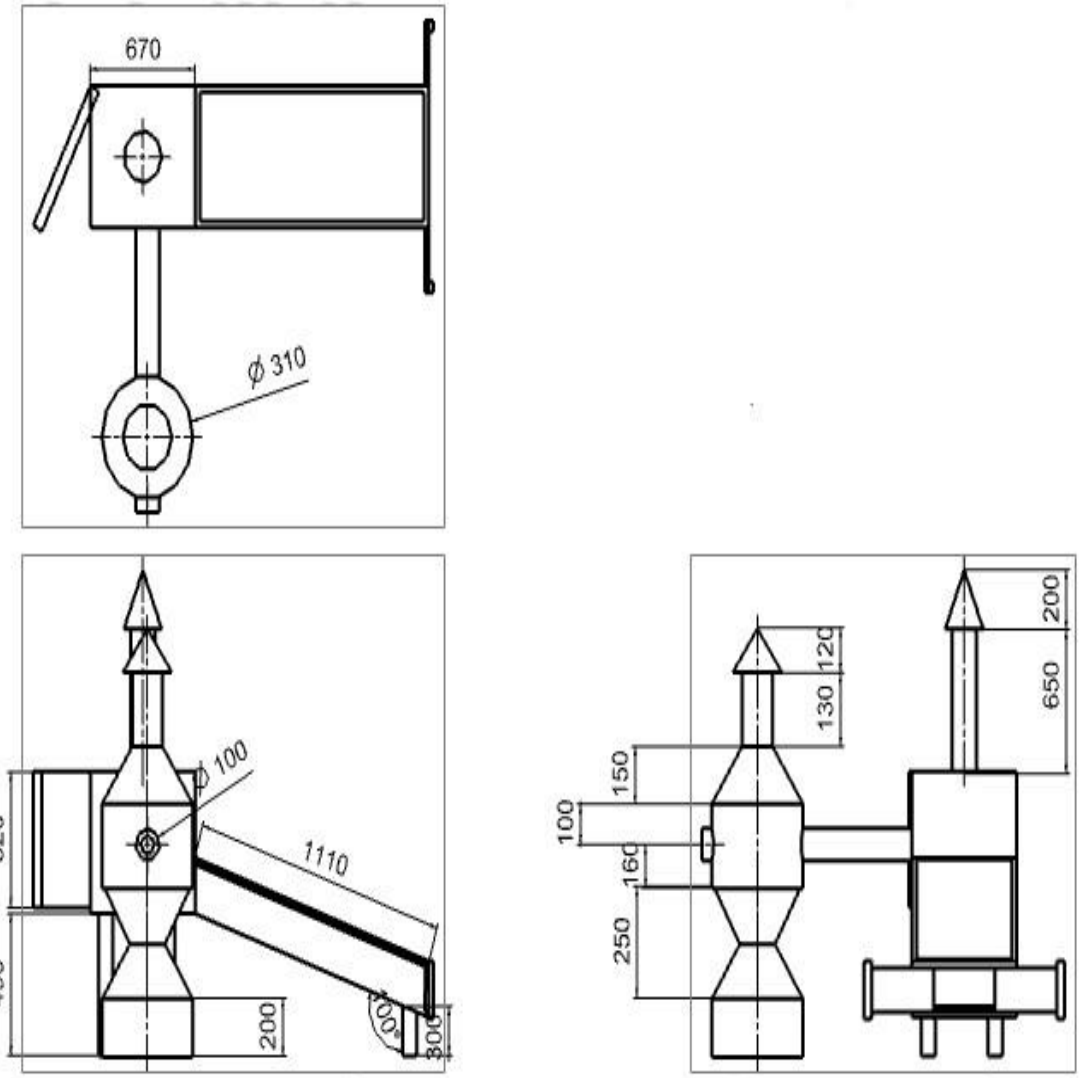

Fig. 3.2. Side view of the dryer*

*All dimensions are in mm.

Fig. 3.3. Pictorial view of the constructed dryer.

3.2.6. Cost of Dryer

The total cost of constructing the dryer was about GhC 1047.00 (Appendix 9). As per the conversion rate of January - February, 2015 the cost was equivalent to US$ 327.20. Purchasing of different materials for constructing the dryer and labor cost were the main components of the budget requirement.

3.3. Experimental Procedures and Dryer Evaluation

3.3.1. Material Preparation for Drying

Fresh pineapples and mangoes were obtained from the local market in Kumasi. They were then washed, peeled and sliced. According to SolarFlex (2013), slices for very wet foods like pineapple should not be more than 5 mm thick. On the other hand, FAO (1997) suggests the slice thickness for pineapple should be 2-3 mm. For the tests that were performed, approximate slice thickness of 4 mm of pineapples and mangoes were used. The fresh produce was arranged in a single layer to avoid moisture being trapped in the lower tray.

3.3.2. Instruments Used for Data Collection

The parameters measured during the evaluation of the solar dryer included weight of the material to be dried, temperature, humidity, wind speed and solar insolation. The temperature and humidity inside the dryer and collector as well as the ambient temperature were measured using Tinytag data loggers, EasyLog – USB 2and HI 91610C Thermohygrometer. The thermometer and the hygrometer were set to record data every one hour. After the end of each test it was taken out and the data was transferred to a computer; for measuring the solar insulation and wind speed measurement Solar Power Meter TM-206, TENMARS and EA-3010U Anemometer were used. Additional data was also obtained from Solar Lab (KNUST).

The weight scale used was SOEHNLE. The initial weight of the fruit to be dried was measured before putting it in the dryer. Once the drying process started, the produce being dried was taken out from the dryer every three hours for the weight or moisture loss to be checked.

3.3.3. Dryer Evaluation Tests

Evaluation of the solar dryer with and without the backup heater was done using three different tests. Each test is described below.

3.3.3.1. No Load Test

The first performance test was the no load test, where the temperature in the dryer was measured without materials to be dried. The temperature variation at the collector output, in drying chamber and ambient temperature values were recorded every one hour interval.

Doing the no load test helped to know the maximum possible temperature rise in the drying chamber as compared to the corresponding ambient value. Parameters such as temperature and solar radiation recorded during this test were used to determine the collector efficiency.

No load test was also performed using the backup heater. This test was carried out after sunset from 18:00 Hour to 21:00 Hour, which helped to know the temperature rise that could be obtained while using only the backup heater. Charcoal was used as the feedstock on the stove. About 300 gm of charcoal was added to the stove every one hour interval.

3.3.3.2. Solar Drying Test

Loaded test of the solar dryer was carried out using 1 kg of fresh slices of pineapple and mango. The slices were laid on a single layer over each tray. This helped to avoid overlapping and ensure uniform drying. From the different tests carried out it was found that 2 – 2.5 kg of pineapple each with about 5 – 8 mm diameter and 1.5 – 2 kg of mango can be dried in a single batch.

Only solar energy was used as heat source for drying during this test. Ambient temperature and humidity, dryer temperature and collector output temperature were recorded every one hour interval while the weight of the produce kept in the dryer was measured every three hour interval.

Oven drying was used to determine the initial moisture content of pineapple and mango as 87.0 % and 85.0 %, respectively. Using these values of initial moisture contents and measuring the weight at regular interval enabled the determination of the moisture loss of the produce during the course of the drying. Wet basis moisture tells the weight of water as a percentage of total weight of a sample and dry basis indicates the weight of water contained in a given weight of dry solids (Mercer, 2014). As a result, moisture content was determined in terms of both wet basis and dry basis. Drying was continued until no further weight reduction was recorded.

The performance of the dryer was also evaluated using drying efficiency and drying rate. These values are used to compare the different loaded tests carried out.

3.3.3.3. Solar Drying in Hybrid Mode Test: Backup Heater used only in the Evening

Another test carried out during evaluation of the solar dryer was with the inclusion of the backup heater. In this case, solar drying was used during the day time. The backup heater was made to supply heat to the drying chamber only during the evening period starting from 18:00. Charcoal was fed to the stove to generate heat every one hour interval until 21:00.

3.3.3.4. Solar Drying in Hybrid Mode Test: Backup Heater used during Day Time and in the Evening

In this test, drying was carried out while the backup heater was supplying heat to the drying chamber during the day time and in the evening from 18:00 Hour to 21:00 Hour. All measurements taken in the previous tests were repeated in this test. Based on these parameters, the drying period, drying rate and drying efficiency were compared with the previous tests.

CHAPTER FOUR: RESULTS AND DISCUSSION

After completing the construction of the dryer, different tests were performed in order to evaluate its performance. Pineapple and mango were dried during the test period. The result of different tests performed are presented below.

4.1. No Load Test

A typical no-load test temperature variation over 24 hours is shown in Fig. 4.1.

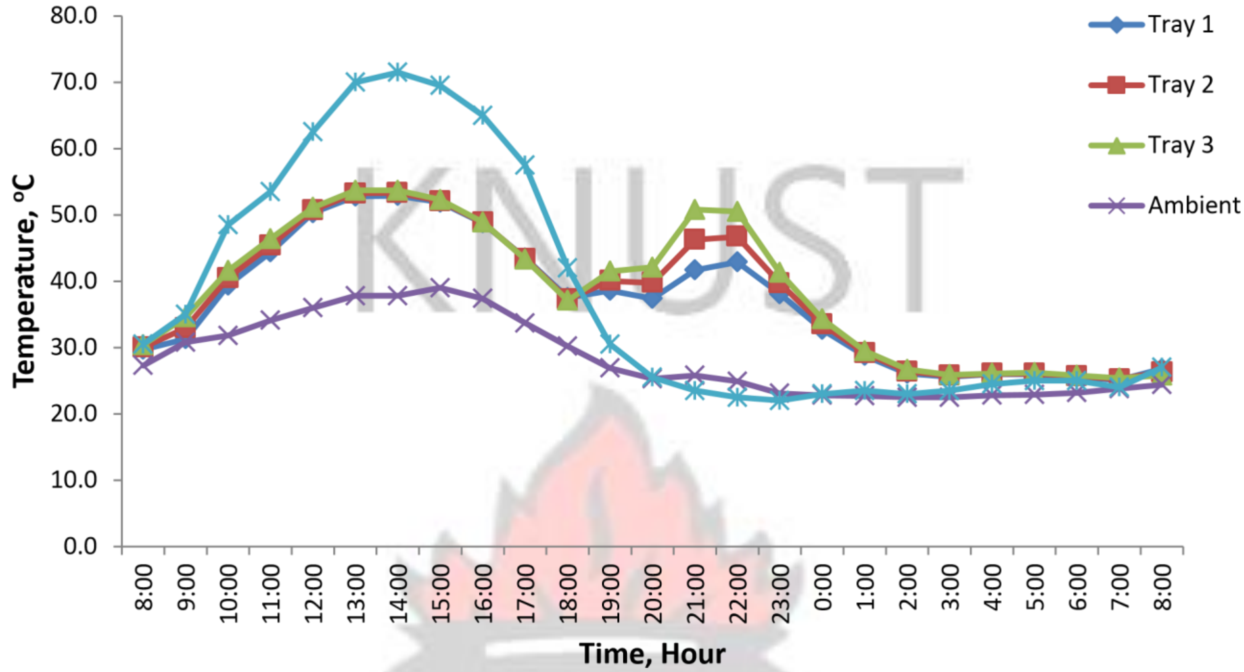

Fig. 4.1. Temperature variation with time for no load test.

During the day time when the sun was the only source of heat supply, a maximum temperature of 71.5°C was attained by the collector output after six hours while the average collector temperature from 08:00 to 17:00 Hour was 56.4 °C. The collector reached its peak temperature value when the ambient temperature was 37.8 °C. The maximum average temperature rise on the trays was about 53.3 °C. This indicates that the maximum rise in temperature of the dryer was about 15.5°C more as compared with the ambient temperature. A similar value was reported by Svenneling (2012) for an indirect type of dryer where the temperature rise in the dryer reached 50 °C at midday. The average air temperature in the dryer (45.1 °C) was 10.5°C more than the daily average ambient temperature (34.6 °C) recorded between 8:00 Hour and 17:00 Hour. This value was better than an indirect type dryer constructed by Antwi (2007) which reported an average temperature elevation of 6.9

^{o}C. A similar no-load indirect type dryer test performed by Alonge and Adeboye (2012) resulted in a maximum temperature elevation of 48 ^{o}C when the ambient temperature was 39 ^{o}C. In addition, a higher drying chamber was reported by (Bolaji, 2005) who designed a box type indirect crop dryer where the maximum average temperature obtained in the drying chamber was 57.0 ^{o}C, while the ambient temperature was 33.5^{o}C.

From Figure 4.1, the trend of the graph shows that the temperature starts to increase from morning and reaches its peak value in the afternoon, where the sun insulation is highest, and starts to descend again in the evening when the sun sets. But, in the evening, the temperature in the dryer was kept higher than the collector or ambient temperature by supplying heat from the backup heater. As a result, the temperature on the bottom tray (tray 3) reached a maximum value of 50.8 ^{o}C after three hours of heat supply. A higher temperature was recorded on the bottom tray which was nearest to the point where heat was supplied from the charcoal stove than the top or middle tray. To maintain this temperature, 300 g of charcoal, costing GhC 0.5 (US$ 0.16), was fed into the stove every one hour interval starting from 18:00 to 21:00 Hours.

4.2. Solar Drying Test

The moisture loss with time for pineapple and mango, when the sun was used as the only source of heat supply, is shown in Fig. 4.2 and 4.3.

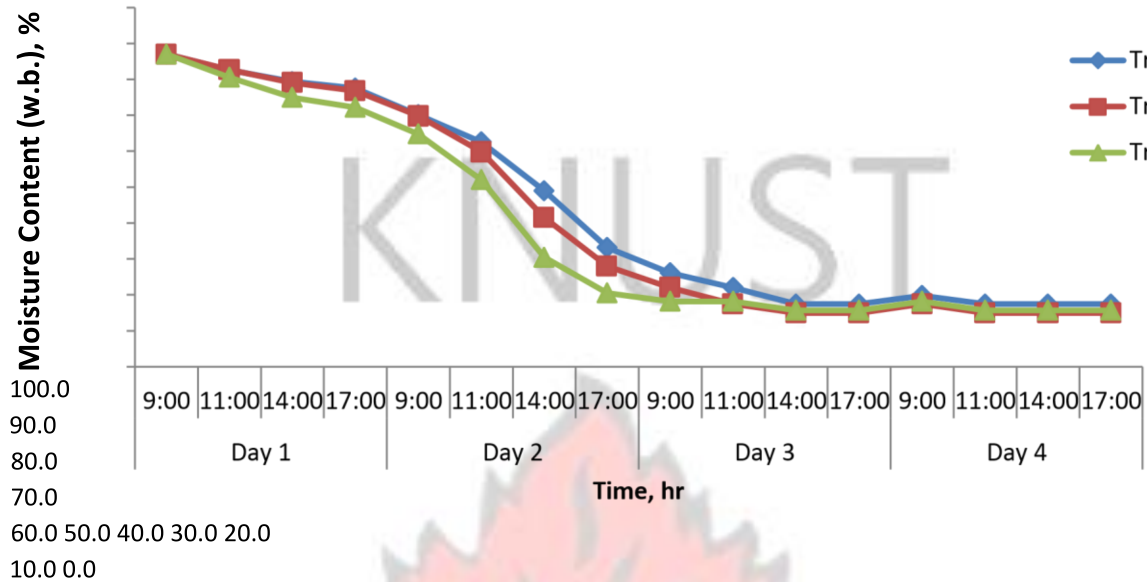

Fig. 4.2. Moisture loss (wet basis) by pineapple with time

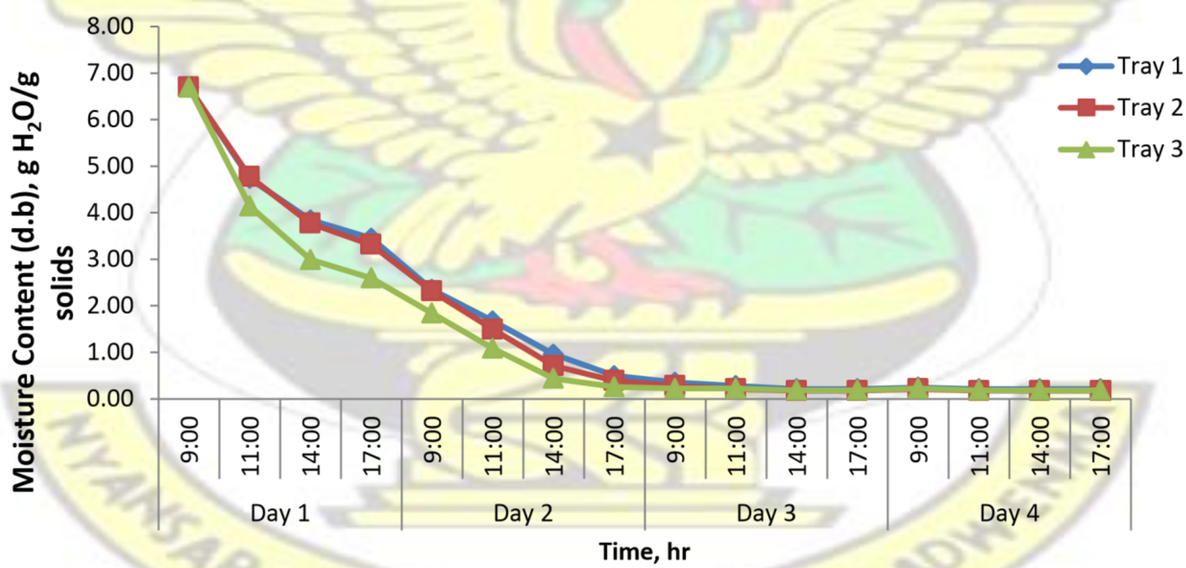

Fig. 4.3. Moisture loss (dry basis) by pineapple with time

As the inlet air passes through the collector and enters the dryer, it will have higher temperature and lower humidity. As the hot air rises in the drying chamber, it picks up moisture from the fruit kept on the trays. This results in reduction of weight or moisture loss of the pineapple. The moisture content of pineapple was reduced from 87 % (w.b.) to 16.0 % (w.b.) or 6.69 g H_2O/g solids (d.b.) to 0.19 g H_2O/g solids (d.b) within almost three days or 23 sunshine hours. The value of the final moisture content fell within the standard range set by Economic Commision for Europe (2013). According to the standard untreated dried pineapple should have final moisture content not exceeding 18.0 % (wet basis).

The drying was continued up to the fourth day but no further reduction in weight was recorded. In order to reduce moisture re-absorption during the night time, the dryer was kept closed using the sliding doors. Even though the dryer was kept closed during the night time, it was observed that moisture re-absorption occurred at the end of the drying period. As a result, the moisture of the pineapple being dried increased by 2.5 % over the night of the third day.

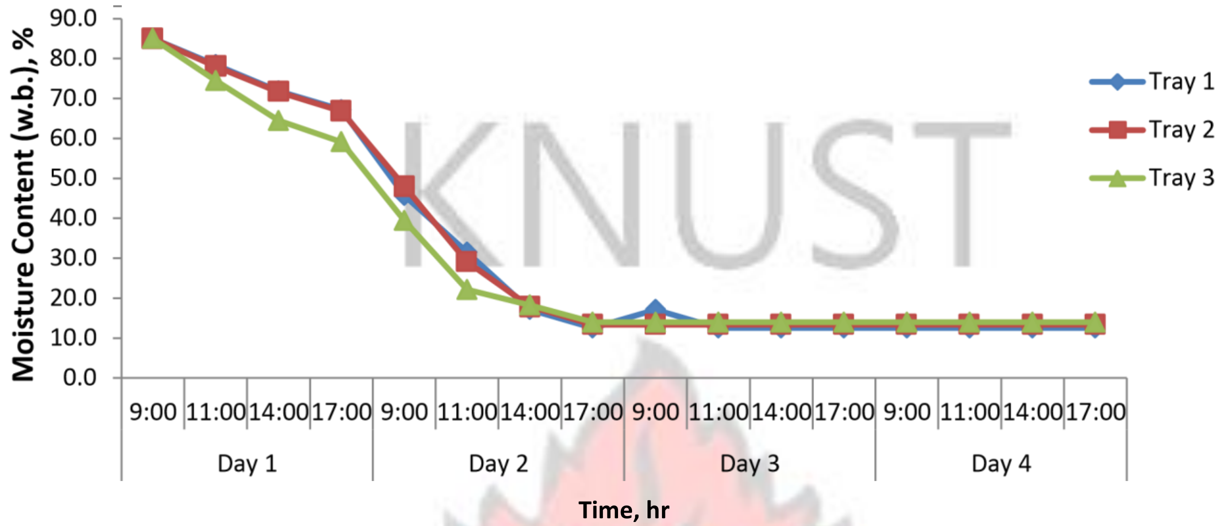

Fig. 4.4. Variation of moisture content (w.b.) with time by mango.

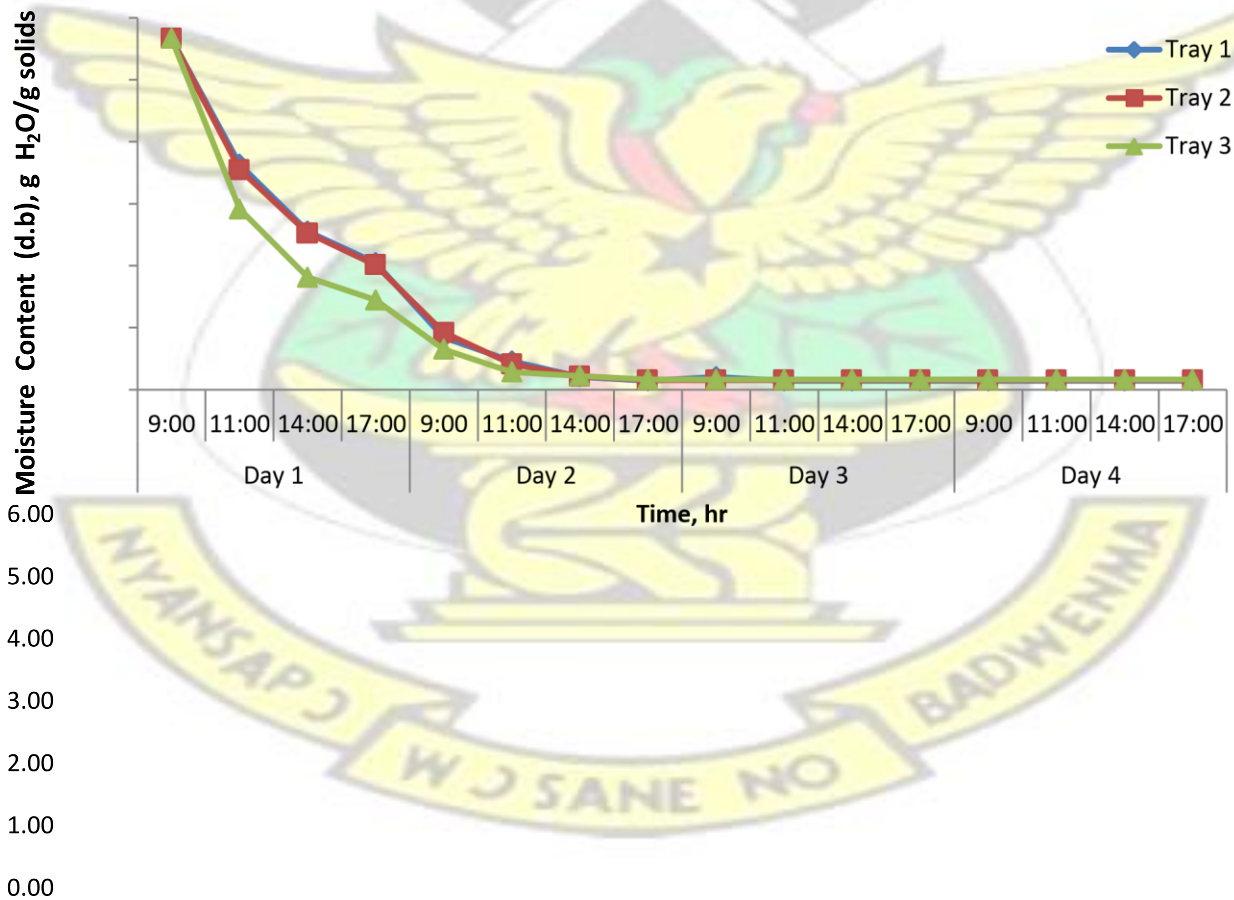

Fig. 4.5. Variation of moisture content (d.b.) with time by mango.

In solar drying of mango, the moisture content of the fruit was reduced from 85.0 % (w.b.) to 13.3 % (w.b) or 5.67 g H_2O/g solids (d.b.) to 0.15 g H_2O/g solids (d.b.) within two days. The value was well in range with the one stated by Economic Commission for Europe (2012) that sets the final moisture content for a dried mango to be not more than 15 % (wet basis).

Although the drying continued up to the fourth day, no moisture loss was observed after the second day. Re-wetting occurred during the night time of the third day of drying. This resulted in moisture re-absorption of about 1.5 %.

A natural convection direct type solar dryer constructed and tested by Akoy *et al.* (2004) reported a moisture reduction from 81.4 % to 10 % w.b. in two days when drying mango. Lower moisture content, i.e. 10 % was achieved within the same drying period as compared to the current dryer constructed. This can be attributed to the fact that a higher drying temperature was recorded in the dryer as a result of direct exposure to the sunlight or direct type of solar dryer.

In both pineapple and mango drying, since the hot air passes through the bottom tray (tray 3) first, the fruit kept on this tray lost its moisture faster than the middle (tray 2) and the top tray (tray 1). Comparing pineapple drying with that of mango drying, mango lost moisture faster than pineapple. This implies less drying time is required for drying mango than pineapple.

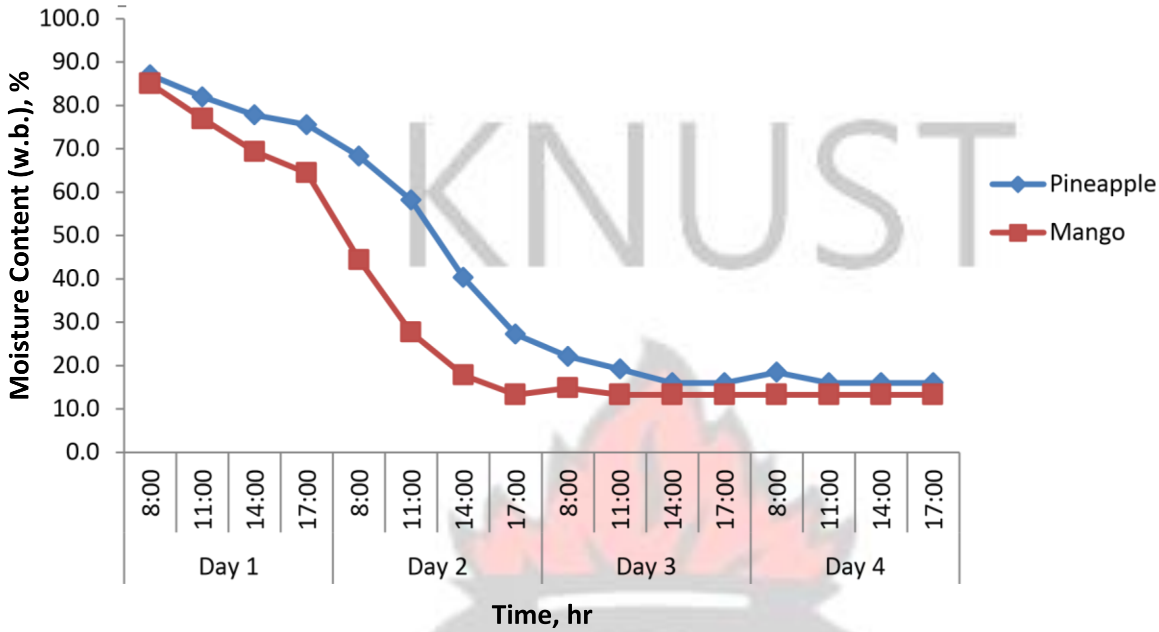

Fig. 4.6. Moisture loss of mango and pineapple with time.

4.3.Solar Drying in Hybrid Mode: Backup Heater used only in the Evening

The temperature and humidity variation for this test are shown below. During the day time, the solar dryer was operated without using the backup heater. The maximum temperature at the collector output and dryer were 71.5ºC and 50.0ºC, respectively, recorded at 14:00 Hour.

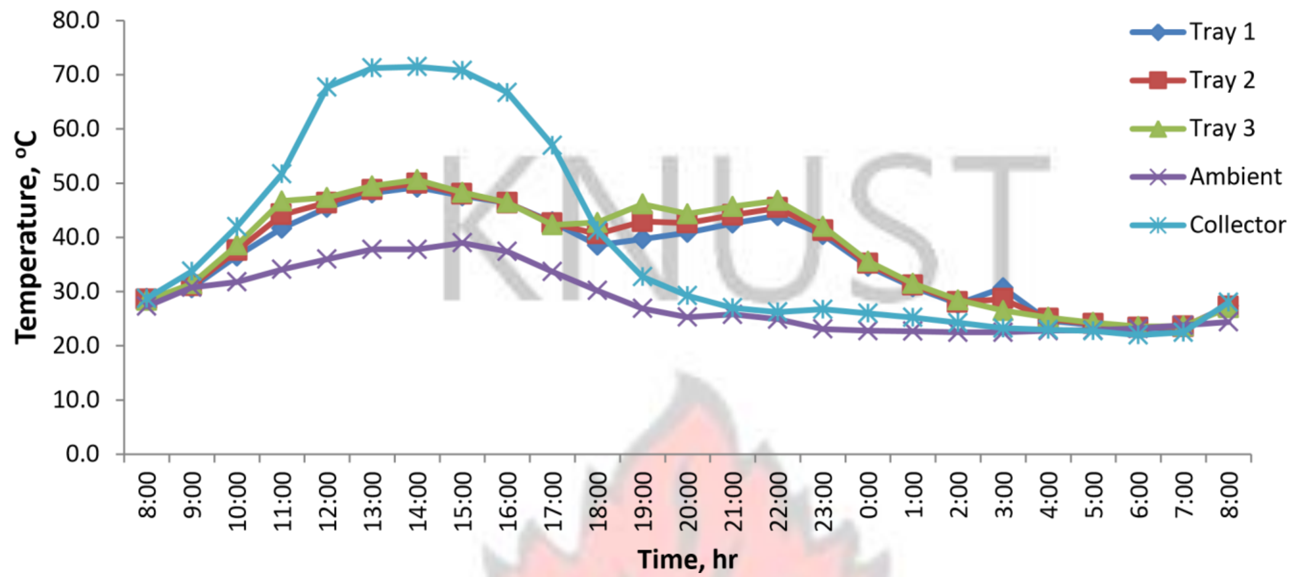

Fig. 4.7. Variation of temperature with time by backup heater in the evening.

In the evening, the temperature in the dryer was kept higher than the collector or ambient by directly supplying heat from the charcoal stove. A maximum average drying temperature of 45.4°Cwas recorded in the dryer after four hours of backup heat supply. Due to the fact that the bottom tray is near to the supply of the heat source, the average temperature on the bottom tray (44.6 °C) was greater than the average temperature of top tray (41.0 °C). This affected the uniformity of drying in the chamber as the slices of fruits kept on the bottom tray dried faster than those kept on top.

The humidity in the drying chamber was kept lower than the collector and ambient humidity as a result of the heat supplied at night. This would reduce moisture reabsorption during the night time and also increase the capacity of the heated air to extract more moisture from the produce being dried. As a result, no moisture re-absorption had occurred during the night time.

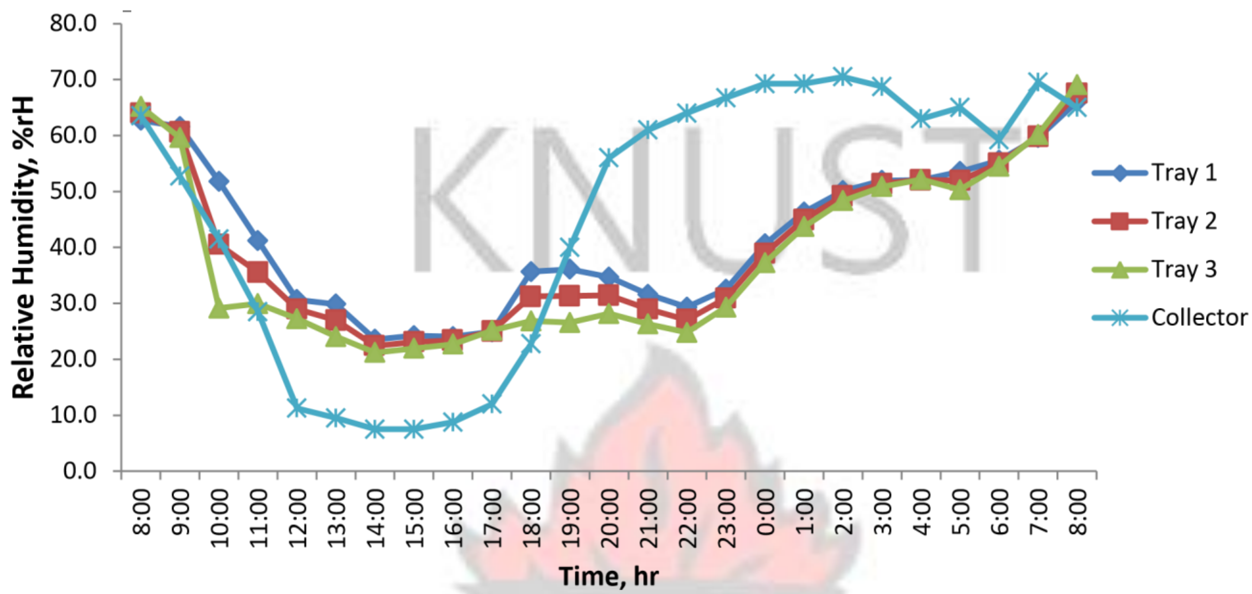

Fig. 4.8. Variation of relative humidity with time of backup heater used in the evening.

Moisture content of pineapple kept in the dryer for this particular test was reduced from 87.0 % (w.b.) to an average value of 16.0 % (w.b.) or 6.69 g H2O/g solids (d.b) to 0.19 g H2O/g solids (d.b.) within almost three days or 23 sunshine hours. From the graph, tray 3 had higher moisture loss rate compared with tray 1 and tray 2.

Although this particular test resulted in the same drying time as that of drying using only solar energy, there is a great difference in moisture loss during the night time. For the first evening of drying using the backup heater, the pineapple lost moisture of about 18.9 % over the night, i.e. until the next morning; whereas the corresponding value for the solar drying was only 7.3 %.

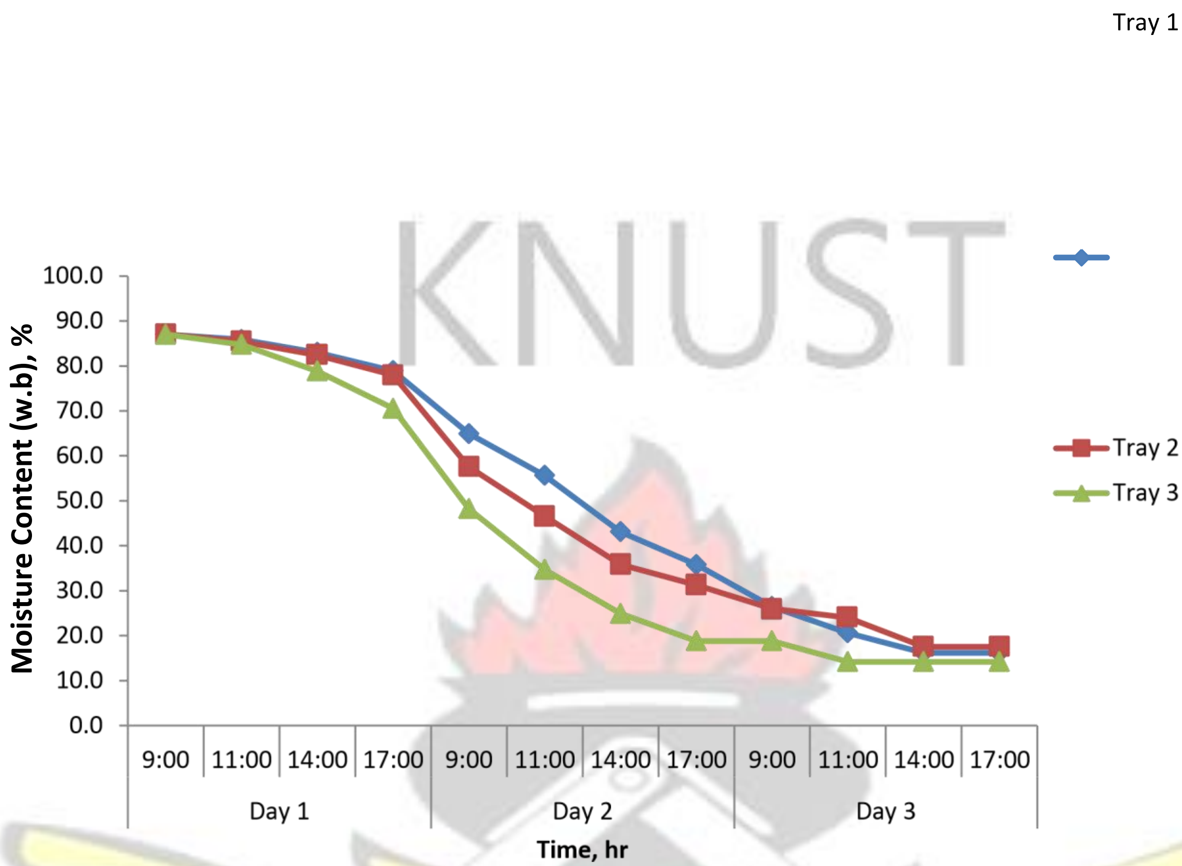

Fig. 4.9. Variation of moisture content (w.b) with time of pineapple using backup heater in the evening.

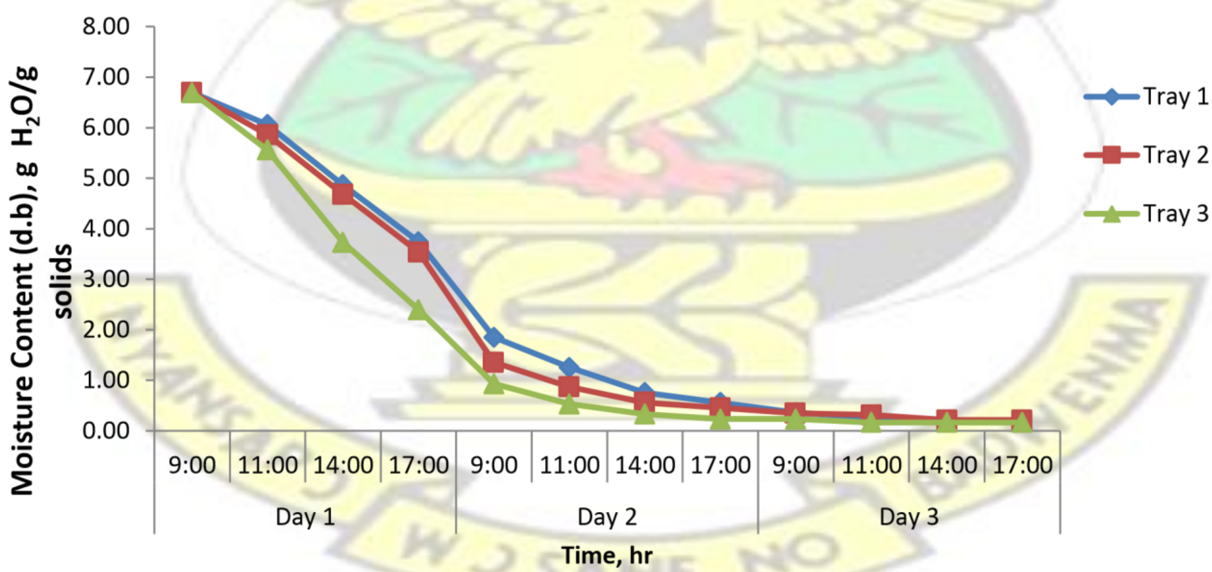

Fig. 4.10. Variation of moisture content (d.b) with time of pineapple using backup heater in the evening.

Similarly, the moisture content for mango was reduced from 85.0 % (w.b.) to 16.4 % (w.b) or 5.67 g H2O/g solids (d.b) to 0.15 g H2O/g solids (d.b) in one and a half day or 14 sunshine hours. The average moisture reduction on wet basis over the first night of drying was calculated to be 33.1 % while for solar drying it was 20 %. Hence, the supply of the backup heater resulted in a extra 13.1 % moisture removal.

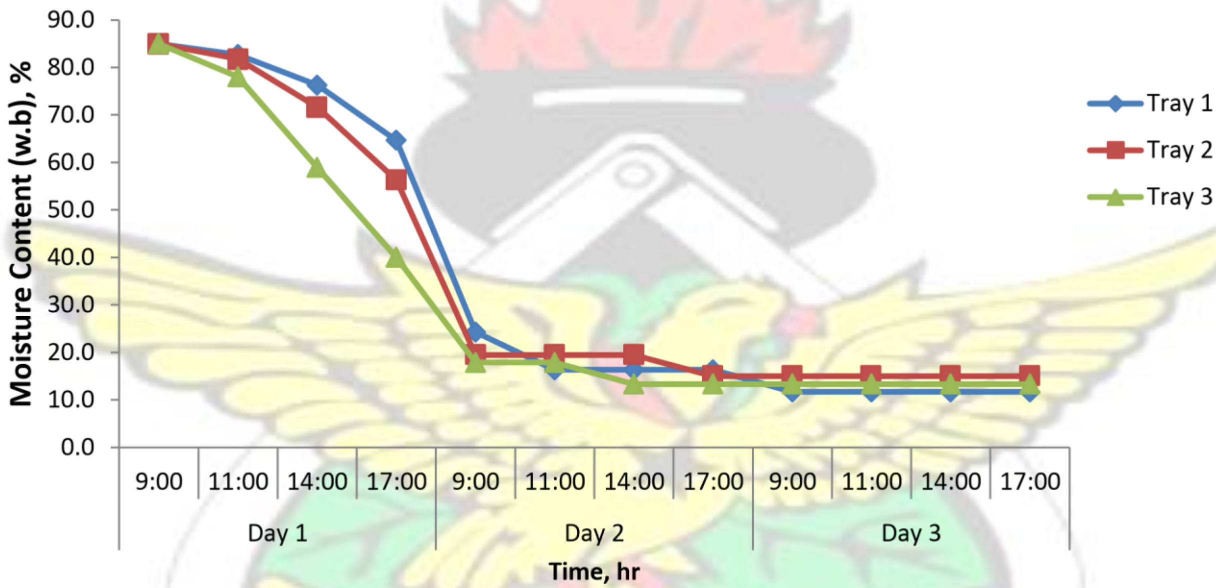

Fig. 4.11. Variation of moisture content (w.b) with time for mango when backup heater is used in the evening.

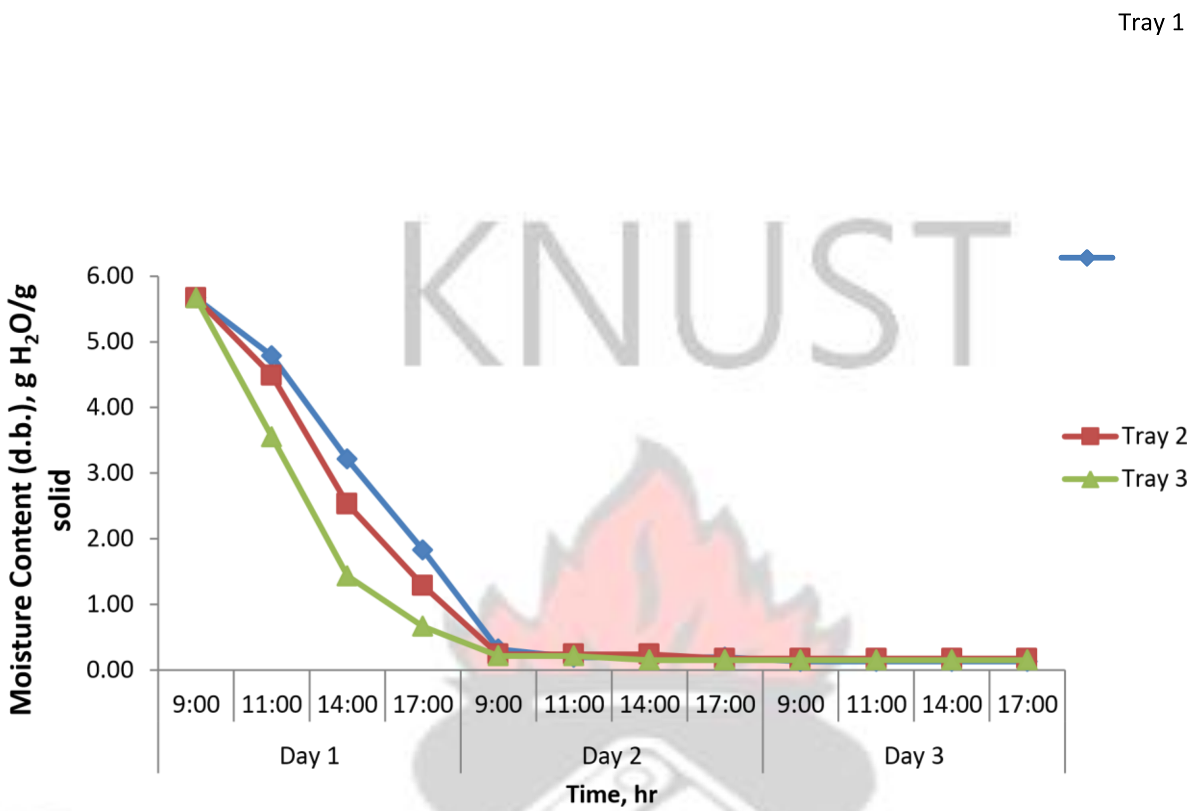

Fig. 4.12. Variation of moisture content (d.b) with time of mango using backup in the evening.

4.4. Solar Drying in Hybrid Mode: Backup Heater used During Day Time and in the Evening

Connecting the backup heater during the day time and supplying heat by burning charcoal can provide a faster drying as compared with using only solar energy. It took 20 sunshine hours to reduce the moisture content of pineapple from 87.0 % (w.b.) to 16.1 % (w.b.) whereas for mango it took almost two days or 14 sunshine hours to reduce the moisture content from 85.0 % (w.b) to 12.7 % (w.b.).

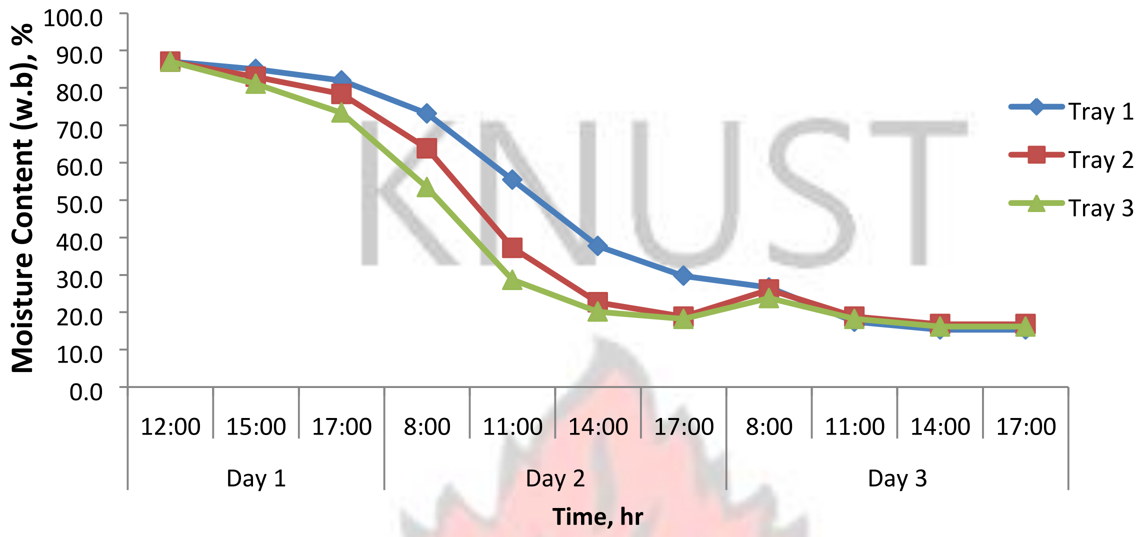

Fig. 4.13. Variation of moisture content (w.b) with time of pineapple using backup heater in the day and evening.

About 300 g of charcoal was supplied every two hour interval during the day time and every one hour during the evening, until 21:00 Hour. The result obtained for this test for drying pineapple was comparable to that reported by Elepano and Satairapan (2001). For this study, it took 18 hours for a solar dryer with biomass stove to dry pineapple from a moisture content of 85 % w.b. down to 20 % w.b. at an average drying temperature of 60 ^{o}C.

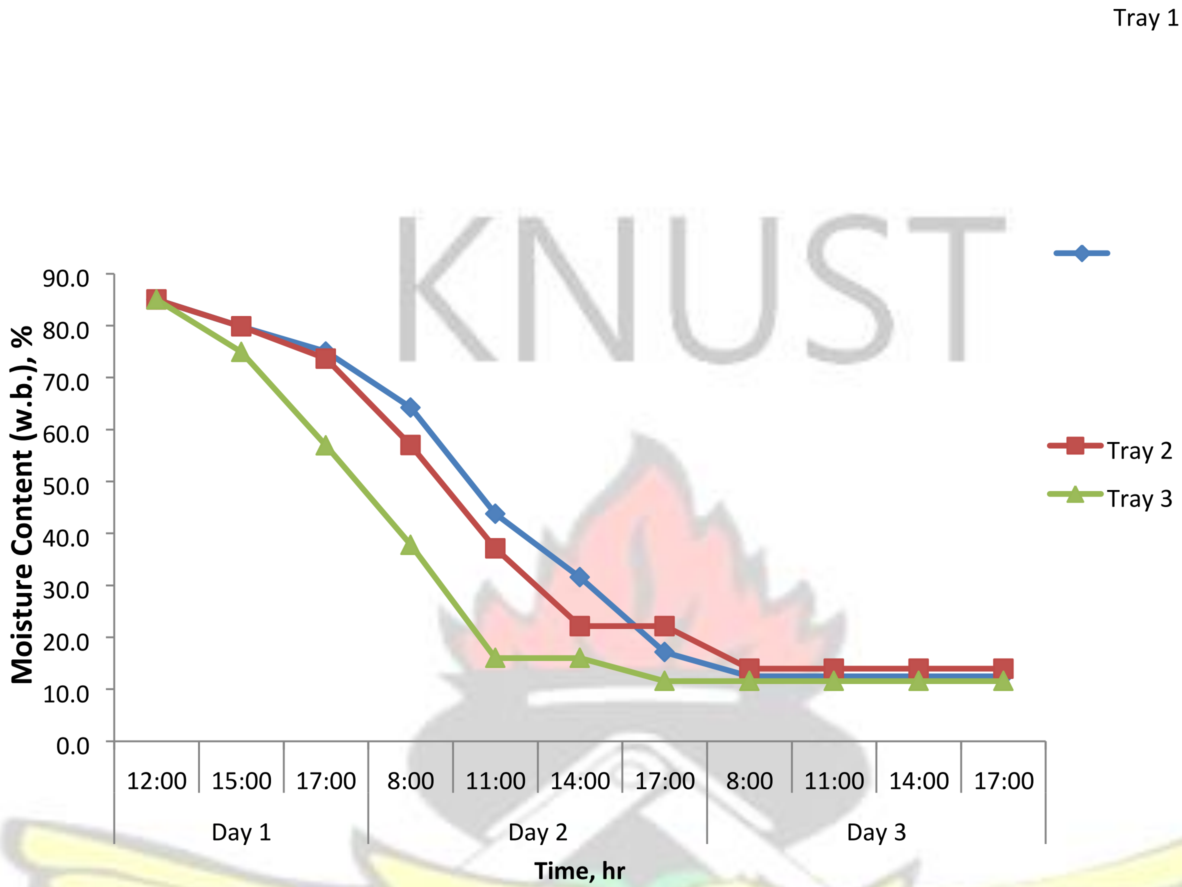

Fig. 4.14. Variation of moisture content (w.b) with time of mango using backup heater in the day and evening.

Figure 4.15 and Figure 4.16 show the moisture loss trend for the different tests carried out during the evaluation of the dryer. From the graph, moisture loss while incorporating the backup heater during the day and night, was faster than the other tests. The moisture loss for the three tests was almost equal up to the 5^{th} hour of drying. But after that, the fruits kept in the dryer where the heat was supplied from both solar and the backup heater started to lose moisture faster. Percentage moisture reduction for the study, Figure 4.15, was about 18.5% between the 5^{th} and 8^{th} hour of drying while for the other two tests it was 5.2 % on average. After two hours of drying on the second day, the moisture content (w.b.) of pineapples being dried using the hybrid mode reached 26.8 % while in the solar drying the corresponding value was 58.2 %.

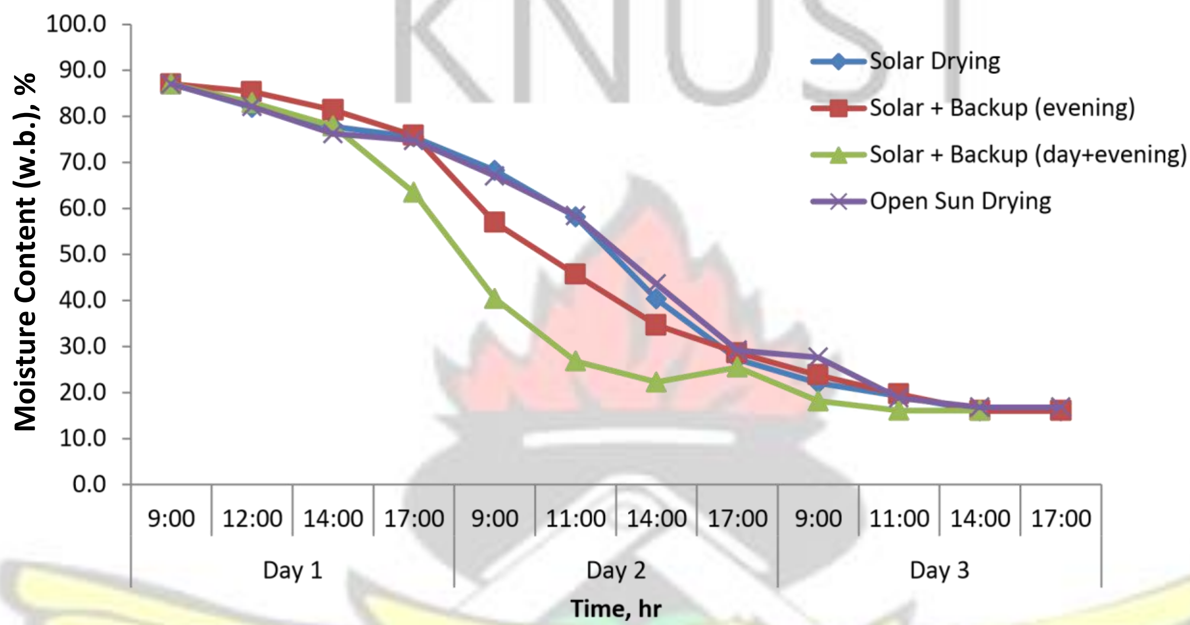

Fig. 4.15. Variation of moisture content (w.b) with time of pineapple for the different tests carried out.

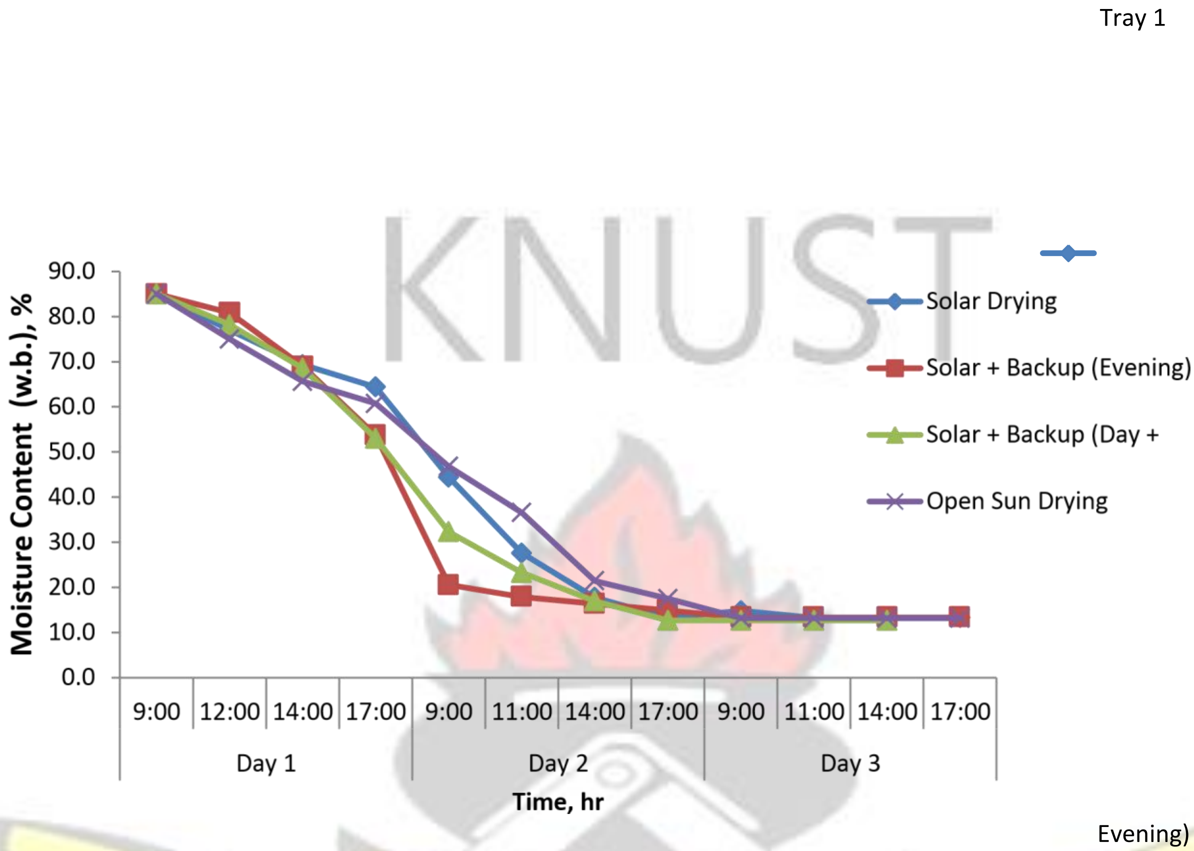

Fig. 4.16. Variation of moisture content (w.b) with time of mango for the different tests carried out.

4.5. Drying Rate

The drying rate for the different tests performed are presented in Table 4.1. For solar drying, the drying rate for pineapple was found to be 23.7g/h whereas for mango it was 15.5 g/h. The drying rate were25.2 g/h and 18.4 g/h for pineapple and mango, respectively, when solar drying was used with the backup heater (evening only). But a higher drying rate was obtained when the backup heater was used with the solar energy during both the day time and in the evening. These results are presented in Table 4.1.

Table 4.1. Drying rate of pineapple and mango for the different drying modes.

Type of Test	Drying Rate, g of H_2O removed/h	
	Pineapple	Mango
Solar Drying	23.7	15.5
Solar Drying + Backup Heater (Evening)	25.2	18.4
Solar Drying + Backup Heater (Day + Evening)	32.5	19.3

In addition, the drying rates for each test in terms of the grams of solids present in the sample are given below.

Table 4.2. Drying rate of pineapple and mango in terms of the dry solid matter for the different drying modes.

Type of Test	Drying Rate, g of H_2O removed/ g solids/h	
	Pineapple	Mango
Solar Drying	0.848	0.973
Solar Drying + Backup Heater (Evening)	0.891	1.024
Solar Drying + Backup Heater (Day + Evening)	0.976	1.130

Table 4.2 shows the drying rate of pineapple and mango in terms of the dry solid matter for different modes of drying. The drying rate in hybrid mode, i.e. when the dryer is used in both day and night time was 13.1 % (pineapple) and 13.8 % (mango) faster than solar drying. It was also 8.7 % (pineapple) and 9.4 % (mango) faster than when backup heater was used only in the evening.

4.6. Collector Efficiency and Drying Efficiency

The collector efficiency calculated using the no load test was found to be 31.7 %. This value is in accordance with Struckmann (2008) that gives a typical flat-plate collector efficiency to be between 25% and 45%. But different literature reported higher values for efficiency of flat plate collectors. One such case is collector efficiency of 46.6 % reported by Saravanan *et al.* (2014). Bolaji (2005) also reported a collector efficiency of 60.5 % for a box-type absorber collector.

The collector was well insulated at the bottom with a thick insulation to avoid heat loss at the bottom. But heat loss might have occurred from the edges of the transparent glass cover of the collector. Hence, collector efficiency for this dryer can be improved by sealing this glass cover over the edges.

The drying efficiency of the solar dryer was found to be 9.7 %. This value is less than the range stated in Brenndorfer *et al.* (1987) which suggest that typical values of drying efficiency should be between 10 - 15 % for natural convection solar dryers. In another report, drying efficiency of 10.8 % was reported by Schiavone (2011) for drying mango in a natural convection solar dryer.

The average drying efficiency when the backup heater was used by burning charcoal was found to be 7.5 % and 8.7 %, for backup heater used in the evening only and throughout the drying time, respectively. This value is less when compared with the one stated by Barki *et al.* (2012), where the average drying efficiency for a dryer with an incinerator that uses charcoal as a feed material was stated to be 13 %. In addition, the drying efficiency when the backup heater is used is less than the solar drying efficiency. The reason for this can be attributed to the fact that the heat that is obtained by burning charcoal does not directly come in contact with the material to be dried, but instead is used to heat a tube of metal which in turn heats the drying air. In addition, the nonuniform drying temperature on the trays also reduces the drying efficiency. The drying efficiency in hybrid mode reported by Barki *et al.* (2012), which is 13 %, was also less than the drying efficiency of the solar dryer.

Table 4.3. Drying Efficiency for different drying modes.

Type of Test	Drying Efficiency, %

Solar Drying	9.7
Solar Drying + Backup Heater (Evening)	7.5
Solar Drying + Backup Heater (Day + Evening)	8.7

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

An indirect type solar dryer with a backup heater was designed and constructed with materials readily available in the market. The dryer is easy to operate and handle. An additional system, backup heater consisting of a charcoal stove, was included in order to make drying continuous throughout the night and cloudy periods.

Under no-load condition, the average collector temperature reached 56.4 ^{o}C and that of the dryer reached 45.1 ^{o}C while the average ambient temperature was 34.6 ^{o}C. When only the backup heater was used in the evening by burning charcoal a temperature as high as 50.8 ^{o}C was recorded on the bottom tray. This indicated that the temperature in the dryer was raised above the ambient temperature creating a suitable condition for drying.

The performance of the dryer was evaluated using pineapple and mango in which the initial moisture contents were reduced from 87 % and 85 % to 16 % and 15.5 %, respectively, within two to three days. A better dryer performance in terms of drying rate was obtained when the dryer was operated in a hybrid mode, i.e. when heat was supplied by burning charcoal as a backup system. As a result, drying rate increased by 26.9 % (pineapple) and 19.8 % (mango) than the drying rate in solar dryer.

The collector efficiency obtained from no load test was 31.5 %. This value is well in the range recommended by different literature for natural convection solar dryers. The drying efficiencies were 9.7 %, 8.7 % and 7.5 % for solar drying, backup heater used throughout the drying period and backup heater used only in the evening.

It was found that the solar dryer can dry high initial moisture content fruits such as pineapple and mango to the recommended value of moisture content for safe storage within two to three days. The solar dryer can be used during any time and season as a result of the heat provided using the backup stove. Hence, it can provide a means of preserving agricultural produce that are harvested in the rainy season.

5.2. Recommendations

The performance of the dryer can further be enhanced by making modifications and following the recommendations given below:

1. The glass cover of the collector should be insulated on the edge. In addition, the gap between the collector and drying chamber should be covered with permanent insulation that can withstand rain.

2. The gap on the drying chamber where the backup heater is attached should be well covered using insulation material when the solar dryer is used with only solar energy as a heat source.

3. Insulating the drying chamber will help to attain a higher drying temperature, especially at night when the backup heater is the only source of heat supply.

4. Design modifications are required to maintain the same amount of drying temperature in the dryer when the backup heater is used. One such suggestion would be to internally extend the metal tube to the adjacent sides of the drying chamber. This would help to minimize the non-uniformity of heat transfer on a tray.

REFERENCES

Akoy, E. O. M., Ismail, M. A. and Ahmed, E. A. and L. W. (2004). Design and Construction of A Solar Dryer for Mango Slices, University of Khartoum, Khartoum, Sudan. Available from <www.tropentag.de/2006/abstracts/full/501.pdf>. [15 February 2014]

Alonge, A. F. and Adeboye, O. A. (2012). Drying Rates of Some Fruits and Vegetables with Passive Solar Dryers. *International Journal of Agricultural and Biological Engineering*, *5*(4): 83–90. DOI: 10.3965/j.ijabe.20120504.0010

Amrutkar, S. K., Ghodke, S. and Patil, K. N. (2012). Solar Flat Plate Collector Analysis. *IOSR Journal of Engineering*, *2*(2): 207–213.

Antwi, K. I. (2007). Comparative Study of Hybrid Solar-gas Crop Dryer. M.Sc Thesis. University of Cape Coast, Ghana. Available from <http://ir.ucc.edu.gh/dspace/handle/123456789/441>. [02 October 2014]

ATPS (2013). *Design and Analysis of a 1MW Grid-Connected Solar PV System in Ghana.* African Technology Policy Studies (ATPS), [Shakespear Mudombi, Mammo Muchie], ATPS RESEARCH PAPER No. 27.

Barki, E., Ibrahim, J.S. and Eloka-Eboka, A. C. (2012). Performance Evaluation of an Efficient Solar Dryer with a Backup Incinerator for Grated Cassava under Makurdi Humid Climate. *International Journal of Environment and Bioenergy*, *2*(2): 131–139.

Basumatary, B., Roy, M., Basumatary, D., Narzary, S., Deuri, U., Nayak, P. and Kumar, N.

(2013). Design , Construction and Calibration of Low Cost Solar Cabinet Dryer. *International Journal of Environmental Engineering and Management*, *4*(4): 351–358.

Bolaji, B. O. (2005). Development and Performance Evaluation of a Box-type Absorber Solar Air Collector for Crop Drying. *Journal of Food Technology*, *3*(4): 595–600.

Brenndorfer, B., Kennedy, L., Oswin Bateman, C. O., Trim, D. S., Mrema, G. C. and WerekoBrommy, C. (1987). Solar Dryers - Their Role in Post-Harvest Processing (2nd edn.), The Commonwealth Secretariat, London. ISBN 0 85092 282 8, 298 p.

Chaiwanichsiri, S., Laohasongkram, K., Thunpithayakul, C. and Mekmanee, S. (1993). Thermophysical Properties of Fresh and Frozen Pineapples: Procedings of Engineering Properties of Foods Workshop, Bangkok, Thailand, September 22-24, 1993.

Dhanushkodi, S., Wilson, V. H. and Sudhakar, K. (2014). Thermal Performance Evaluation of Indirect Forced Cabinet Solar Dryer for Cashew Drying. *American-Eurasian J. Agric. & Environ. Sci.*, *14*(11): 1248–1254.

Duffie, J. A. and Beckman, W. A. (1980). Solar Energy of Thermal Processes (2nd edn.). John Wiley & Sons, Inc, New York, 919 p.

Ecofys (2006). THE GOLD STANDARD : Project Design Document for Gold Standard Voluntary Offset projects, Ghana. 49 p.

Economic Commision for Europe (2012). Draft Standard Concerning the Marketing and Commercial Quality Control of Dried Mangoes, Geneva, 7 p.

Economic Commision for Europe (2013). Revised Draft Standard for Dried Pineapple, Geneva, 9 p.

Ekechukwu, O. V and Norton, B. (1995). Design and Measured Performance of a Solar Chimney for Natural-Circulation Solar-Energy Dryers. Internal Report: International Center for Theoretical Physics, Trieste, Italy.

Elepano, A. R. and Satairapan, K. T. (2001). A Solar-Biomass Dryer for Pineapple: Proceedings of 51st Philippine Society of Agricultural Engineers National Convection, Cebu, Phillipines, April 23-27, 2001.

El-Sebaii, A. A. and Shalaby, S. M. (2012). Solar drying of agricultural products: A Review. *Journal of Renewable and Sustainable Energy Reviews*, *16*(1): 37–43.

Ertekin, C. and Yaldiz, O. (2004). Drying of Eggplant and Selection of a Suitable Thin Layer Drying Model. *Journal of Food Engineering*, *63*(3): 349–359. DOI: 10.1016/j.jfoodeng.2003.08.007

Forson, F. K., Nazha, M. A. A., Akuffo, F. O. and Rajakaruna, H. (2007). Design of MixedMode Natural Convection Solar Crop Dryers: Application of Principles and Rules of Thumb. *Journal of Renewable Energy*, *32*(14): 2306–2319.

FAO (1997). Fruit Processing Toolkit: Dried Fruit. InPho, Food and Agricultural Organization (FAO), New York. (pp. 13).

Fudholi, A., Othman, M. Y., Ruslan, M. H., Yahya, M., Zaharim, A. and Sopian, K. (2011). Design and Testing of Solar Dryer for Drying Kinetics of Seaweed in Malaysia. *Journal of Recent Researches in Geography, Geology, Energy, Environment and Biomedicine*, 119– 124.

GEPC (2005). Market Brief for Mango Export in the United Kingdom. Ghana Export Promotion Council (GEPC), Ghana.

Green, M. G., and Schwarz, D. (2001). Solar Drying Technology for Food Preservation. Gate Information Service/GTZ, Eschborn, Germany. Available from <http://www. armageddononline.org/uploads/Food_-_Solar_Food_Drying.pdf>. [22 June 2014]

Gregoire, R. G. (1984). Understanding Solar Food Dryers, Volunteers in Technical Assistance, Arlington, Virginia, 24 p.

Hii, C.L., Jangam, S.V., Ong, S.P. and Mujumdar, A. S. (Ed.). Solar Drying: Fundamentals, Applications and Innovations. Transport Phenomena Group, Singapore, 2012, ISBN 978981-07-3336-0. p 150.

IAE/UPLB (2002). Solar-Biomass Hybrid Cabinet Dryer. Institute of Agricultural Engineering/University of Philippines Los Banos (IAE/UPLB), Philippines.

Irtwange, S. V. and Adebayo, S. (2009). Development and performance of a laboratory-scale passive solar grain dryer in a tropical environment, *Journal of Agricultural Extension and Rural Development,* 1(2):42–49.

Jercan, A. S. (2006). The Simplified Calculus of the Flat Plate Solar Collector, *Anals of the University of Craiova, Electrical Engineering Series*. (30): 302–306.

Medugu, D. W. (2010). Performance Study of Two Designs of Solar Dryers. *Journal of Applied Science Research, 2*(2): 136–148.

Mercer, D. G. (2007). An intermediate course in food dehydration and drying. Department of

Food Science, University of Guelph, Ontario, Canada. Available from <elearning.iufost.org/sites/default/files/Intermediate-Outline-1.pdf>. [30 September 2014]

Mercer, D. G. (2014). An Introduction to the Dehydration and Drying of Fruits and Vegetables. Department of Food Science, University of Guelph. Ontario, Canada. ISBN 978-0-88955-621-8

MoFA (2011). Statistics, Research and Information Directorate (SRID). Agriculture in Ghana, Facts and Figures, Ministry of food and Agriculture (MoFA), Ghana.

Moujaled, J. K. (2014). A Ccomparative Assessment of Solar Resource Database, Simulations and Ground Observations for Kumasi. M.Sc Thesis. Kwame Nkrumah University of Science and Technology, Kumasi, Ghana. Available from <http://ir.knust.edu.gh/bitstream/123456789/6508/1/Jalel%20kobina%20Moujaled.pdf>. [10 December 2014]

Mujumdar, A. S. (Ed.). (2006). Handbook of Industrial Drying (3rd edn.), Taylor & Francis Group, LLC, Singapore. 1282 p.

Mustayen, A. G. M. B., Mekhilef, S. and Saidur, R. (2014). Performance Study of Different Solar Dryers: A Review. *Journal of Renewable and Sustainable Energy Reviews*, *34*(1): 463–470.

Raju, R. V. S., Reddy, R. M. and Reddy, E. S. (2013). Design and Fabrication of Efficient Solar Dryer. *Journal of Engineering Research and Applications*, *3*(6): 1445–1458.

Ringeisen, B., M. Barrett, D. and Stroeve, P. (2014). Concentrated Solar Drying of Tomatoes. *Journal of Energy for Sustainable Development*, *19*:47–55.

Sanni, L. O., Onadipe-Phorbee, O. and Alenkhe, E. B. (2012). Low-cost Sustainable Cassava Drying Technologies in West Africa: A Compendium of Inforation, Design, Fabrication and Pilot Testing. IITA/CFC-WA Project Report, Nigeria. 28 p.

Saravanan, D., Wilson, V. H. and Kumarasamy, S. (2014). Design and Thermal Performance of the Solar Biomass Hybrid Dryer for Cashew Drying. *Journal of Mechanical Engineering*, *12*(3): 277–288.

Saxena, A. and Goel, V. (2013). Solar Air Heaters with Thermal Heat Storages, *Chinese Journal of Engineering*, Volume 2013, Article ID 190279 .

Scanlin, D. (1997). The Design, Construction and use of an Indirect, Through-pass, Solar Food Dryer. Homebrew (Vol. 57, p. 22). Appalachian. Available from <http://www.homepower.com/view/?file=HP57_pg62_Scanlin>. [02 August 2014]

Schiavone, D. F. (2011). Development and Evaluation of a Natural-Convection Solar Dryer for Mango in Rural Haitian Communities. M.Sc Thesis. University of Florida, USA.

Seveda, M. S. (2013). Design of a Photovoltaic Powered Forced Convection Solar Dryer in NEH Region of India, *International Journal of Renewable Energy Research, 3*(4): 1–7.

SolarFlex (2013). Drying Fruits and Vegetables with the SolarFlex Dryer. Technical Specifications of SolarFlex Small Farm Dryer. Available from <http://www.postharvest.org/Drying%20Fruits%20and%20Vegetables%20with%20the%20SolarFlex%20Dryer.pdf>. [15 December 2014]

Spillman, C. K. (1980). Capturing and Storîng Energy From the Sun. Hayes, I. J (Ed.), *Cutting Energy Costs* (pp. 330–341). Kansas State University, Washington D.C.

Stiling, J., Li, S., Stroeve, P., Thompson, J., Mjawa, B., Kornbluth, K. and Barrett, D. M. (2012). Performance Evaluation of an Enhanced Fruit Solar Dryer Using Concentrating Panels. *Journal of Energy for Sustainable Development*, *16*(2): 224–230.

Struckmann, F. (2008). Analysis of a Flat-plate Solar Collector. Project Report: 2008 MVK 160 Heat and Mass Transport. Lund University, Lund, Sweden.

Svenneling, J. (2012). Constructing a Solar Dryer for Drying of Pineapples: Implementing a Solar Dryer for Sustainable Development in Ghana. Karlstands University, Netherlands.

Weiss, W. and Buchinger, J (2002). Solar Drying. Austrian Development Cooperation, Austria. Available from <http://t.aee-intec.at/0uploads/dateien553.pdf>. [17 June 2014]

Zakari, A. K. (2012). Ghana National Mango Study. PACT II Program and International Trade Centre Ghana.

APPENDIX 1: Sample Analysis of Moisture Content

Day	Time	Sunshine Hour	Pineapple Slice Weight (g) Tray 1	Solid Weight (g)	Moisture Weight (g)	Wet Basis Moisture (%)	Dry Basis Moisture (g H_2O/g solids)
Day 1	9:00	0	216	28.08	187.92	87.0	6.69
	11:00	2	161	28.08	132.92	82.6	4.73
	14:00	5	136	28.08	107.92	79.4	3.84
	17:00	8	125	28.08	96.92	77.5	3.45
Day 2	9:00	9	94	28.08	65.92	70.1	2.35

	11:00	11	75	28.08	46.92	62.6	1.67
	14:00	14	55	28.08	26.92	48.9	0.96
	17:00	17	42	28.08	13.92	33.1	0.50
Day 3	9:00	18	38	28.08	9.92	26.1	0.35
	11:00	20	36	28.08	7.92	22.0	0.28
	14:00	23	34	28.08	5.92	17.4	0.21
	17:00	26	34	28.08	5.92	17.4	0.21
Day 4	9:00	27	35	28.08	6.92	19.8	0.25
	11:00	29	34	28.08	5.92	17.4	0.21
	14:00	32	34	28.08	5.92	17.4	0.21
	17:00	35	34	28.08	5.92	17.4	0.21

Day	Time	Sunshine Hour	Pineapple Slice Weight (g) Tray 2	Solid Weight (g)	Moisture Weight (g)	Wet Basis Moisture (%)	Dry Basis Moisture (g H_2O/g solids)
Day 1	9:00	0	216	28.08	187.92	87.0	6.69
	11:00	2	162	28.08	133.92	82.7	4.77
	14:00	5	134	28.08	105.92	79.0	3.77
	17:00	8	121	28.08	92.92	76.8	3.31
Day 2	9:00	9	93	28.08	64.92	69.8	2.31
	11:00	11	70	28.08	41.92	59.9	1.49
	14:00	14	48	28.08	19.92	41.5	0.71
	17:00	17	39	28.08	10.92	28.0	0.39
Day 3	9:00	18	36	28.08	7.92	22.0	0.28
	11:00	20	34	28.08	5.92	17.4	0.21
	14:00	23	33	28.08	4.92	14.9	0.18
	17:00	26	33	28.08	4.92	14.9	0.18
Day 4	9:00	27	34	28.08	5.92	17.4	0.21
	11:00	29	33	28.08	4.92	14.9	0.18
	14:00	32	33	28.08	4.92	14.9	0.18
	17:00	35	33	28.08	4.92	14.9	0.18

Day	Time	Sunshine Hour	Pineapple Slice Weight (g) Tray 3	Solid Weight (g)	Moisture Weight (g)	Wet Basis Moisture (%)	Dry Basis Moisture (g H_2O/g solids)
Day 1	9:00	0	214	27.82	186.18	87.0	6.69
	11:00	2	143	27.82	115.18	80.5	4.14
	14:00	5	111	27.82	83.18	74.9	2.99
	17:00	8	100	27.82	72.18	72.2	2.59
Day 2	9:00	9	79	27.82	51.18	64.8	1.84
	11:00	11	58	27.82	30.18	52.0	1.08
	14:00	14	40	27.82	12.18	30.5	0.44
	17:00	17	35	27.82	7.18	20.5	0.26
Day 3	9:00	18	34	27.82	6.18	18.2	0.22
	11:00	20	34	27.82	6.18	18.2	0.22
	14:00	23	33	27.82	5.18	15.7	0.19
	17:00	26	33	27.82	5.18	15.7	0.19
Day 4	9:00	27	34	27.82	6.18	18.2	0.22
	11:00	29	33	27.82	5.18	15.7	0.19
	14:00	32	33	27.82	5.18	15.7	0.19
	17:00	35	33	27.82	5.18	15.7	0.19

Day	Time	Sunshine Hour	Mango Slice Weight (g) Tray 1	Solid Weight (g)	Moisture Weight (g)	Wet Basis Moisture (%)	Dry Basis Moisture (g H_2O/g solids)
Day 1	9:00	0	105	15.75	89.25	85.0	5.67
	11:00	2	73	15.75	57.25	78.4	3.63
	14:00	5	56	15.75	40.25	71.9	2.56
	17:00	8	48	15.75	32.25	67.2	2.05
Day 2	9:00	9	29	15.75	13.25	45.7	0.84
	11:00	11	23	15.75	7.25	31.5	0.46
	14:00	14	19	15.75	3.25	17.1	0.21
	17:00	17	18	15.75	2.25	12.5	0.14
Day 3	9:00	18	19	15.75	3.25	17.1	0.21
	11:00	20	18	15.75	2.25	12.5	0.14

	14:00	23	18	15.75	2.25	12.5	0.14
	17:00	26	18	15.75	2.25	12.5	0.14
Day 4	9:00	27	18	15.75	2.25	12.5	0.14
	11:00	29	18	15.75	2.25	12.5	0.14
	14:00	32	18	15.75	2.25	12.5	0.14
	17:00	35	18	15.75	2.25	12.5	0.14

Day	Time	Sunshine Hour	Mango Slice Weight (g) Tray 2	Solid Weight (g)	Moisture Weight (g)	Wet Basis Moisture (%)	Dry Basis Moisture (g H_2O/g solids)
Day 1	9:00	0	104	15.6	88.4	85	5.67
	11:00	2	71	15.6	55.4	78.0	3.55
	14:00	5	55	15.6	39.4	71.6	2.53
	17:00	8	47	15.6	31.4	66.8	2.01
Day 2	9:00	9	30	15.6	14.4	48.0	0.92
	11:00	11	22	15.6	6.4	29.1	0.41
	14:00	14	19	15.6	3.4	17.9	0.22
	17:00	17	18	15.6	2.4	13.3	0.15
Day 3	9:00	18	18	15.6	2.4	13.3	0.15
	11:00	20	18	15.6	2.4	13.3	0.15
	14:00	23	18	15.6	2.4	13.3	0.15
	17:00	26	18	15.6	2.4	13.3	0.15
Day 4	9:00	27	18	15.6	2.4	13.3	0.15
	11:00	29	18	15.6	2.4	13.3	0.15
	14:00	32	18	15.6	2.4	13.3	0.15
	17:00	35	18	15.6	2.4	13.3	0.15

Day	Time	Sunshine Hour	Mango Slice Weight (g) Tray 3	Solid Weight (g)	Moisture Weight (g)	Wet Basis Moisture (%)	Dry Basis Moisture (g H_2O/g solids)
Day 1	9:00	0	109	16.35	92.65	85.0	5.67
	11:00	2	64	16.35	47.65	74.5	2.91
	14:00	5	46	16.35	29.65	64.5	1.81

	17:00	8	40	16.35	23.65	59.1	1.45
Day 2	9:00	9	27	16.35	10.65	39.4	0.65
	11:00	11	21	16.35	4.65	22.1	0.28
	14:00	14	20	16.35	3.65	18.3	0.22
	17:00	17	19	16.35	2.65	13.9	0.16
Day 3	9:00	18	19	16.35	2.65	13.9	0.16
	11:00	20	19	16.35	2.65	13.9	0.16
	14:00	23	19	16.35	2.65	13.9	0.16
	17:00	26	19	16.35	2.65	13.9	0.16
Day 4	9:00	27	19	16.35	2.65	13.9	0.16
	11:00	29	19	16.35	2.65	13.9	0.16
	14:00	32	19	16.35	2.65	13.9	0.16
	17:00	35	19	16.35	2.65	13.9	0.16

APPENDIX 2: Typical Temperature and Humidity Variation with time During No-Load Test

Hour	Ambient Temp. ºC	Ambient Humidity %	Collector Temp. ºC	Collector Humidity %	Dryer Temperature (ºC)			Dryer Humidity (%)		
					Tray 1 (Top)	Tray 2 (Middle)	Tray 3 (Bottom)	Tray 1 (Top)	Tray 2 (Middle)	Tray 3 (Bottom)
8:00	27.3	79.6	30.5	50.0	29.7	30.1	30.4	53.5	52.7	51.9
9:00	30.8	77.4	35.0	47.5	31.3	33.0	34.6	43.5	44.6	45.7
10:00	31.8	74.1	48.5	24.5	39.4	40.5	41.6	30.3	30.7	31.1
11:00	34.1	65.3	53.5	14.0	44.4	45.4	46.4	24.0	22.8	21.5
12:00	36.0	64.5	62.5	7.0	50.3	50.7	51.1	15.7	15.3	14.9
13:00	37.8	73.6	70.0	4.0	52.8	53.3	53.7	11.9	11.3	10.6
14:00	37.8	94.3	71.5	2.5	52.9	53.3	53.7	10.5	9.7	9.0
15:00	39.0	88.5	69.5	2.0	51.9	52.1	52.3	9.6	8.8	8.0
16:00	37.4	90.3	65.0	2.5	48.8	48.9	48.9	11.0	10.5	9.9
17:00	33.7	89.2	57.5	5.0	43.5	43.4	43.3	13.1	12.8	12.5
18:00	30.2	90.4	42.0	12.0	37.5	37.3	37.1	21.8	22.6	23.3
19:00	26.9	91.5	30.5	34.0	38.6	40.1	41.5	22.1	21.3	20.5
20:00	25.3	94.1	25.5	37.5	37.4	39.8	42.1	20.8	19.2	17.5
21:00	25.8	95.2	23.5	44.5	41.7	46.3	50.8	18.6	15.9	13.2
22:00	24.9	94.6	22.5	50.0	42.9	46.7	50.5	19.1	17.0	14.9
23:00	23.1	94.1	22.0	53.0	38.1	39.7	41.3	22.1	20.7	19.3
0:00	22.8	93.8	23.0	59.5	32.7	33.5	34.3	34.9	34.5	34.1
1:00	22.7	94.8	23.5	67.5	28.8	29.2	29.5	40.9	41.5	42.0
2:00	22.5	94.9	23.0	63.5	26.1	26.4	26.7	43.8	45.1	46.3
3:00	22.5	95.6	23.5	72.5	25.6	25.8	25.9	51.3	54.7	58.1
4:00	22.8	95.4	24.5	76.0	26.0	26.1	26.1	53.2	56.1	58.9
5:00	22.9	95.1	25.0	75.0	26.0	26.1	26.2	51.1	53.6	56.1
6:00	23.2	94.7	25.0	76.0	25.5	25.7	25.8	47.3	47.6	47.9
7:00	23.8	91.8	24.0	72.5	25.1	25.3	25.4	47.8	47.6	47.4

8:00	24.4	92.0	27.0	71.0	26.8	26.3	25.8	57.1	57.5	57.8

APPENDIX 3: Solar Insulation, W/m^2 (Solar Lab, KNUST)

Hour	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10
8:00	111.77	8.6	51.59	51.59	154.76	0	0	120.37	0	34.39
9:00	77.38	128.97	292.33	214.95	369.71	0	42.99	335.32	283.73	464.29
10:00	404.1	163.36	541.67	464.29	558.86	395.5	318.12	550.26	507.27	232.14
11:00	670.63	429.89	687.83	636.24	696.43	395.5	627.64	687.8	722.22	799.6
12:00	670.63	739.42	283.73	687.83	756.61	696.43	679.23	756.61	748.01	773.81
13:00	653.44	713.62	249.34	85.98	842.59	722.22	567.46	696.43	713.62	730.82
14:00	550.26	601.85	111.77	206.35	223.54	593.25	567.47	610.45	601.85	619.05
15:00	171.96	283.73	42.99	464.29	335.32	300.93	378.31	412.7	438.49	455.69
16:00	94.58	214.95	51.59	85.98	180.56	103.17	180.56	214.95	206.35	232.14

Average Solar Insulation = 394.8 W/m^2

APPENDIX 4: Chemical Composition of Fresh pineapple and mango

Pineapple

Component	Content (%)
Moisture	85.75 ± 0.52
Carbohydrate	14.29 ± 0.30
Protein	0.47 ± 0.01
Fiber	0.45 ± 0.03
Ash	0.30 ± 0.04
Fat	0.04 ± 0.01

Source: Chaiwanichsiri *et al.*, 1993

Mango

Component	Content (%)
Moisture	81.7
Carbohydrate	17.0
Protein	0.51
Fiber	1.8
Ash	0.5
Fat	0.27

Source: USDA, 2001

APPENDIX 5: Gyapa stove Sizes, Dimensions and Applications

Stove Size Description	Dimensions (cm)		Typical Application
	Height	Top Diameter	
Small	21.0± 0.5	26.5± 0.5	Domestic use
Medium	25.0± 0.5	32.0± 0.5	Both domestic and non domestic (commercial or institution) applications
Large	38.5± 0.5	47.5± 0.5	Exclusively for commercial application

Source: Ecofys, 2006

APPENDIX 6: Cost of the Solar Dryer

	Name of Part	Material and Dimensions	Quantity	Unit Price	Amount, GhC	Amount, USD*
1	Drying Chamber and collector casing	Plywood 3quarter; 240x120x2 cm	2	60.00	120.00	37.50
2	Sliding Door	Plywood 1/8; 240x120x0.5 cm	1	25.00	25.00	7.80
3	Dryer Support	Wood 2x2; 4.5x4.5x420	4	10.00	40.00	12.50
4	Collector Glazing or Transparent material	Glass; 1100x660x5 mm	1	50.00	50.00	15.60
5	Chimney and Stove Cover	Galvanized sheet 1.16; 4x8 ft	1	120.00	120.00	37.50
6	Drying Tray	Stainless steel; ½ sheet, 2x4 ft	1	290.00	290.00	90.60
7	Insulation	Glass wool			50.00	15.60
8	Gypa Stove		1	25.00	25.00	7.80
9	Air inlet and Chimney cover	Mosquito net, 1 yard	1	5.00	5.00	1.60
10		Screws, 1quarter	1 pack	6.00	6.00	1.90
11		Screws, 4 quarter	1 pack	10.00	10.00	3.10
12		Adhesive for wood	1	45.00	45.00	14.10
13		Door hinge	1 pair	3.50	3.50	1.10
14		Door lock	3	5.00	15.00	4.70
				Total	805.00	251.6
15	Labor cost, 30%				242.00	75.60
				Grand Total	1047.00	327.20

* Conversion rate of 1 USD = 3.2 GhC (as of January - February 2015)