THE DESIGN AND EVALUATION OF A GREENHOUSE TYPE SOLAR DRYER AND ITS PERFORMANCE ON TWO FOOD COMMODITIES: CASSAVA AND COCOA

BY

LOUISA OFOSUAH OBIMPEH

(10282822)

THIS THESIS IS SUBMITTED TO THE UNIVERSITY OF GHANA, LEGON IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE AWARD OF MPHIL FOOD SCIENCE DEGREE

JULY, 2018.

DECLARATION

I declare that this work was conducted by me under supervision in the Department of Nutrition and Food Science, University of Ghana.

………………………………………………… ……………………….

LOUISA OFOSUAH OBIMPEH DATE

(Student)

………………………………………………… ………………………

PROF. SAMUEL SEFA-DEDEH DATE

(Supervisor)

.... ………………………..

PROF. F.K. SAALIA DATE

(Supervisor)

.... ………………………..

DR. NICOLE SHARON AFFRIFAH DATE

(Supervisor)

ABSTRACT

Drying, a process for food preservation involves subjecting a food commodity to high temperatures that aid in the removal of moisture thereby making the food shelf stable. The objective of this study was to design a greenhouse type solar dryer that would be used for the drying of cassava and other foods and evaluate the characteristics of the dried products. The rationale behind this study was that open sun drying has been the method of drying over the centuries but it is subjected to a lot of challenges such as contamination from bird droppings and rodents, high moisture content due to inconsistent temperature variations which contributes to microbial contamination as a result of the slow or intermittent drying and no protection from rain or dew. The greenhouse type solar dryer with a total volume and surface area of 20.335 m^3 and 35.774 m^2 respectively was designed and constructed with locally available materials. Temperature and humidity were monitored in the empty greenhouse type solar dryer (GTSD) and open sun drying (OSD) for a period of 14 days showed that the GTSD recorded the highest temperature of 60^oC occurring between 12:00 and 13:00 hours GMT. The highest relative humidity was recorded at 84 % and this was observed at a later time in the day, 18:00 hours GMT. Cassava slices (0.47cm thickness) and chunks (4 cm length × 2 cm breadth × 1.5 cm) and cocoa beans were dried. The total drying period for the two food commodities was 156 hours. Generally, there was moisture removal in all the dried samples. However the GTSD gave a faster drying rate of 3.361 g/g h for the slices occurring after 12 hours of initial drying than the OSD. An Analysis of variance performed on the moisture data delineating time of drying, drying method and sample size showed that the removal of moisture of the cassava samples is dependent on the time for drying, the drying method and sample size. The data observed for both moisture and drying rate of the cassava and cocoa samples depicted that drying does not occur at nightfall but rather moisture absorption due to higher humidity levels observed at night.

To further determine the influence of drying on the samples, some laboratory analyses such as pasting property, water activity, colour profile and particle size determination were performed on the resultant dried cassava flour samples and bean cut test and free fatty acid determination on the cocoa beans. The flours emanating from the two drying systems generally had similar characteristics. The cassava slices under the GTSD demonstrated a better quality than the chunks in terms of colour and particle size. Generally the SD_{50} values for flours from the slices were finer than those from the chunks. Values of 120 and 92 for the cassava flours from slices dried in the open sun and GTSD and 150 and 135 for the flours from the chunks were obtained. To further evaluate the efficiency of the GTSD, a mathematical modelling on Henderson and Pabis and Logarithmic models. From the data on the two models, the Henderson and Pabis better explains the drying concept of the dried samples than the logarithmic model. The Henderson and Pabis model gives a better efficient drying system for the dried cassava and cocoa beans because it provided the higher coefficient correlation constant for the cassava slices, chunks and cocoa beans of 0.9991, 0.9989 and 0.9990 respectively thereby depicting a better drying model to be used.

DEDICATION

This research work is dedicated to my late parents Mr. Alfred-Jones Obimpeh & Ms. Rosina Boakye and Mrs. Florence Ali also of blessed memory.

ACKNOWLEDGEMENT

I thank God Almighty for his mercies throughout this project. I acknowledge my supervisors, Prof. Samuel Sefa-Dedeh for his immense financial and intellectual support and assistance coupled with dedicated supervision and Prof. F.K. Saalia and Dr. Nicole Sharon Affrifah for their assistance and supervision which made it possible for me to complete this project work. I also acknowledge Prof. Kwaku Tano-Debrah for the immense support he provided towards this project. I appreciate all who contributed in shaping this work especially the staff of the Nutrition and Food Science Department, University of Ghana.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ILLUSTRATIONS

LIST OF APPENDICES

CHAPTER ONE

1.0 INTRODUCTION

1.1. Drying

Postharvest losses of food remain one of the challenges in agriculture. Preservation mainly involves the extension of the storage period of a product with the desired quality. Several systems and methods such as drying, salting, fermentation, canning and low temperature processing (refrigeration and freezing) have been adopted for such purposes.

Generally food spoilage is caused by the presence of moisture and the action of molds, yeasts, bacteria and some enzymes and can occur in various stages in the food system e.g. harvesting, handling, transportation, storage and marketing (Prakash *et al*, 2017). Drying of food commodities has been a technique for food preservation since ancient times. Drying is a simple and most accessible widespread processing technology in Africa which involves mainly the removal of water from food commodities.

In Ghana, drying by exposure of the food to direct sunshine (open sun drying) and solar drying are widely used. According to Fudholi *et al.* (2010), open sun drying is subjected to several challenges such as:

i. Contamination from bird droppings and rodents
ii. Mold growth as a result of slow or intermittent drying and no protection from rain or dew
iii. Relatively high moisture content due to inconsistent temperature variations
iv. Reduction in the quality (colour, vitamins) of food products due to ultra-violet (UV) bleaching

v. Drying rate inconsistencies associated with food products due to unfavorable climatic conditions.
vi. Large land space required for spreading food products
vii. Labor intensive due to constant turning of food products and movements of the drying trays during rainfalls.

Kumar *et al.* (2016) made similar observations. Solar drying has been considered therefore as a better option and there have been several approaches to the development and application of this process for the improvement of food safety.

1.1.1. Solar drying

To combat the deficiencies of open sun drying, the first idea of a solar dryer was developed by Everitt and Stanley in 1976 (i.e. a box shaped housing unit having a transparent sunlight cover) (Ekechukwu, 1999). Solar drying is the removal of moisture from a product by heating up the air to a temperature range of 50^{o}C to 60^{o}C using the solar radiations inside a solar dryer which facilitates the extraction of moisture from the products in the drying chamber. Solar drying under controlled conditions of temperature and moisture removing rate ensures a perfect drying and desirable product quality (Janjai and Bala, 2012).

Generally solar dryers are classified according to their operating temperature, heating source, mode of air movement (hot air circulation mechanism), air flow direction (ventilation), type of product and area available for heating air (Tiwari, 2016). Solar dryers are broadly classified in three categories as summarized in Figure 1.

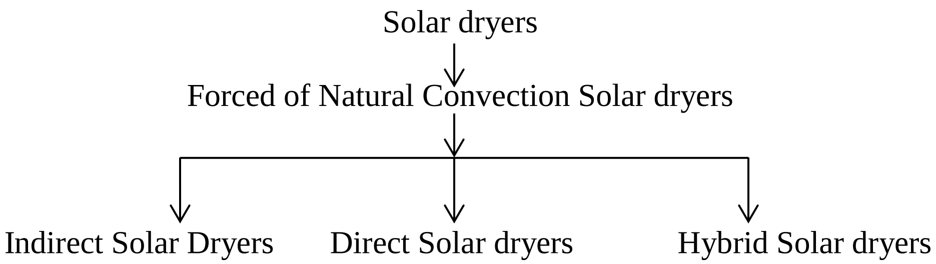


Figure 1: Classification of Solar dryers (Source: Kumar *et al.*, 2016)

According to Hii *et al.* (2012), some of the advantages of solar drying are;

i. The food is enclosed in the dryer is protected from dust, insects, birds and rodents.
ii. The higher temperature, movement of the air and lower humidity increases the rate of drying
iii. Solar dryers are designed to be waterproof therefore the food does not need to be moved when it rains
iv. Solar dryers can be constructed from locally available materials.
v. The higher heat generated in the solar dryer deters insects and aids faster drying that reduces spoilage caused by microbial contamination.

Various designs of solar dryers have been constructed and used in agricultural food drying under the classification in Figure 1. One of such design is the Greenhouse type Solar dryer.

1.1.2. The Greenhouse type solar dryer

Greenhouse dryers are used for different purposes in the agricultural food chain including crop cultivation and drying. The greenhouse solar dryer uses the principle of greenhouse effect, that is, allowing short wavelength solar radiations from the sun to come in and trapping the long wavelength solar radiations (Singh *et al.*, 2018; Chauhan *et al.*, 2016). Various researches and modifications have been carried out to improve the greenhouse solar dryer's performance. Greenhouse solar dryers have been extensively discussed and classified on the following basis (Singh *et al.*, 2018).

a. Airflow

b. Covering material

c. Structure

d. Floor

e. North wall

In further detail from Figure 2, there are various design options and specifications that are added on to the original design of the greenhouse solar dryer.

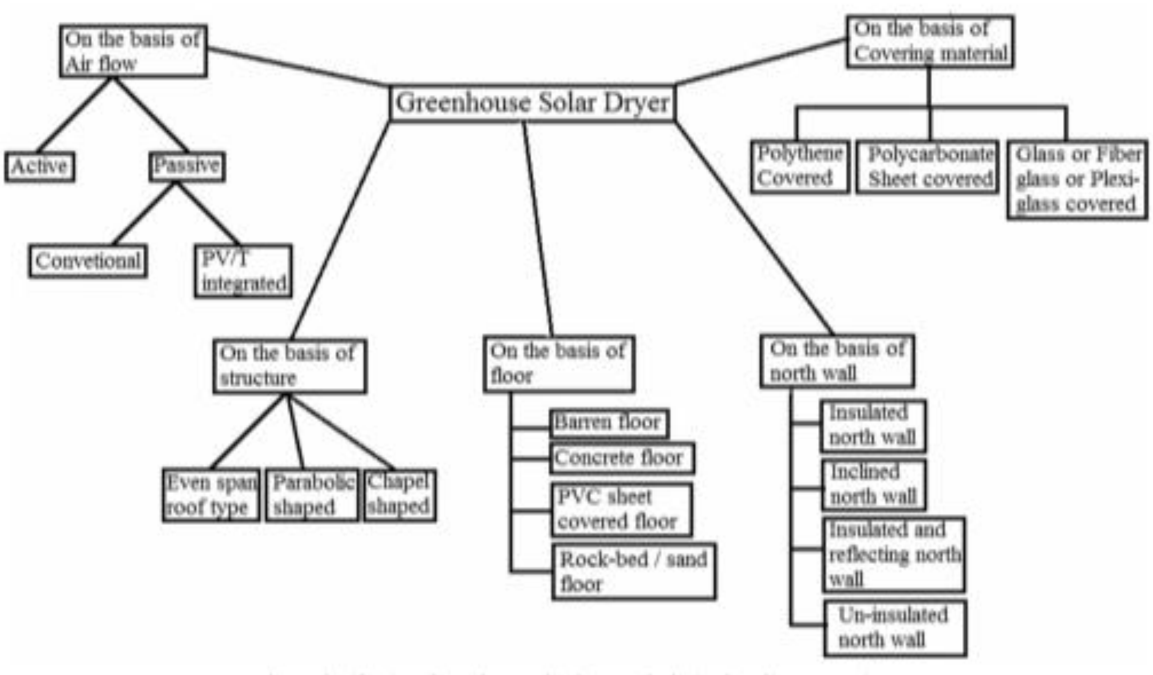


Figure 2: Classification of Greenhouse Solar Dryers (Source: Singh *et al.*, 2018)

1.2. Objectives

The predominant use of open sun drying in Ghana generally affects the quality of the dried products and the amount of agricultural produce that can be handled. Crops such as maize and other cereals, root crops, fruits and vegetables and cocoa are dried. It is envisaged that the design and introduction of the greenhouse type solar dryer into the Ghanaian agribusiness sector will enhance drying performance and improves the throughput and quality of dried materials.

The main objectives of this study were to design and construct a greenhouse type solar dryer using locally available materials and evaluate its efficiency and performance using cassava chips as the primary drying material.

1.3. Specific Objectives

The specific objectives were:

i. To design and construct a Greenhouse type solar dryer (GTSD) using local materials and evaluate the temperature and Humidity changes in the dryer
ii. Compare the performance of the Greenhouse type solar dryer with Open sun drying for cassava.
iii. Evaluate drying efficiency by developing a mathematical model for the drying process using the greenhouse type solar dryer and evaluate some quality indices of flour derived from the cassava chips.
iv. To ferment cocoa beans and to do preliminary drying evaluation using the greenhouse solar dryer.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Drying

Drying of agricultural products counteracts the spoilage activity of various microscopic organisms (Pushpendra *et al.*, 2018). Crops after being dried can be stored for a longer period without getting deteriorated. Other advantages of drying to the product are enhanced product quality and low post harvest losses. In Ghana and other developing countries, food commodities are dried mainly in the open sun. The food commodities are laid either on the bare floor or on wooden mats and exposed directly to the sun. These food products undergoing the open sun drying get contaminated with pest infestation and dirt. Some of the food may be lost to other rodents, birds and other animals.

Various drying systems have been developed to manage the delivery of shelf stable foods globally. These include the bin, tray, drum, fluidized bed, spray and freeze dryers. Most of these dryers require fuel, mechanical and electrical energy during their operation thus making them expensive to use (Mulato and Mühlbauer, 2016).

2.1.1 Mechanism of Drying

There is evidence that certain groups of products exhibit the same drying tendencies (Tefera *et al.*, 2013). Despite the difference in product type and structure, the mechanism of drying can be classified into six general theories on the mechanism of liquid flow within the product (Purandare *et al.*, 2013). These are

i. Diffusion
ii. Capillary flow

iii. Gravity
iv. Convection
v. External pressure (Porous theory)
vi. A sequence of vaporization condensation phenomena induced by a temperature.

Diffusion consists of a redistribution of internal molecules on a product which is brought about by its internal molecular motion of translation and mutual bombardment. Diffusion can only occur when the material or product undergoing the drying operation remains isotropic and homogenous without shrinkage.

Capillarity is the flow of a liquid through interactions and over the surface of a solid due to molecular attraction between the liquid and the solid. This attractive force between the solid and liquid molecules is called the adhesion tension and it's responsible for wetting the product. At the surface of the dried product, an unbalanced force of attraction called surface tension is observed when it comes into contact with a vapor or gas (Fudholi *et al.,* 2010).

The theory of the gravitational force explains that the force of gravity tends to act vertically and pulls water to the bottom of the product (Mortezapour *et al.,* 2012). The theory of convection further explains that there is a movement of moisture induced by a temperature gradient. The flow of moisture always occurs in the direction of decreasing temperature. This theory is only practical when there is a combined effect attributed by capillary suction, external pressure and gravity. The resultant effect renders the product porous which allows the movement of moisture.

In the theory of vaporization condensation, temperature differences are believed to cause vapor pressure gradients within a solid which results in evaporation of the liquid and its subsequent condensation on a colder surface. An example of this theory is when a wet solid is heated at its bottom surface and dry air is circulated over the top, vaporization may occur at the bottom where the temperature is the highest and the vapor diffusing upward may be repeatedly condensed and vaporized before finally escaping as vapor into the air (Mortezapour *et al.*, 2012). There is also the transfer of heat to provide the necessary latent heat of vaporization required for drying.

Fortes and Okos (1980) suggested that drying rate during the constant rate period can be calculated by the equation below:

$$\frac{\mathrm{dM}}{\mathrm{dT}} = \frac{\mathrm{h_T A_p (T_a - T_w)}}{\mathrm{L}}$$

$\frac{\mathrm{dM}}{\mathrm{dT}} = \text{Rate of drying}$

$\mathrm{h_T} = \text{Convective heat transfer coeefficient}$

$\mathrm{A_p} = \text{Surface area of product}$

$\mathrm{T_a} = \text{Dry bulb Temperature of drying air}$

$\mathrm{T_w} = \text{Wet bulb Temperature of air at the surface of the material}$

$\mathrm{L} = \text{Heat of Vaporisation of water}$

There is also a certain point in the drying process known as the critical moisture content where there is insufficient free water to maintain the maximum drying rate. The remaining water in the product is bound water which is held within its cell structure by covalent bond. At this point the rate of moisture removal from the surface of the food product falls progressively and consequently the drying rate declines. This stage of the drying process is the falling rate period. Unlike the constant rate period, the falling rate period is mainly influenced by internal parameters of the food product. These internal parameters of the food product are often combined and expressed as a diffusion coefficient or a drying constant. Drying rate during falling rate period according to Mujumdar *et al.* (2010) is illustrated by:

$$\frac{\mathrm{M} - \mathrm{M_e}}{\mathrm{M_o} - \mathrm{M_e}} = \mathrm{e}^{-\mathrm{kt}}$$

Where

M = Moisture content

$\mathrm{M_e}$ = Equilibrium moisture content

$\mathrm{M_o}$ = Initial moisture content

k = drying constant

t = time

$*$ $\mathrm{M_e}$ and k can be found in research literature eg Hull (1957) for many crops.

2.2 Drying rate

The rate at which a food commodity dries is a vital parameter in selecting a drying method. According to Tefera *et al.*, (2013), when the moisture content of a product at successive time intervals is plotted against time, the pattern shows a decreasing drying rate and a constant drying rate. In simple terms, drying rate is the rate at which moisture is lost from a product. Drying rate (dry basis) can be determined by

$$Drying\ rate, RD = \frac{\Delta M_i}{100\ \times \Delta t} \qquad (kg_w/kg_d\ h)$$

ΔM_i *and* Δt *is the moisture loss over the period and the change in time respectively.*

The drying rate is taken on the basis of 100 kg dry matter of the product.

Drying as a process entails a series of steps in which drying rate plays a role (Amer *et al.*, 2009). Figure 3 shows typical drying rate curve for constant drying conditions. Drying commences with initial moisture content and requires the highest drying rate for its moisture removal. The product at this phase called the transient phase is ultimately wet both within and on the surface. At point C which represents an equilibrium temperature condition of the product surface, the material contains so much water that the liquid surface will dry in a manner that can be equally related to an open faced water. There is a diffusion of moisture from within the product such that a saturated surface condition is maintained and as long as this lasts, evaporation of moisture takes place at a constant rate. When a solid material is dried under constant drying conditions, the moisture content typically falls. From point 1 to 2 the product experiences a constant rate drying period which will proceed until the free moisture appears from the surface making the moisture removal progressively less.

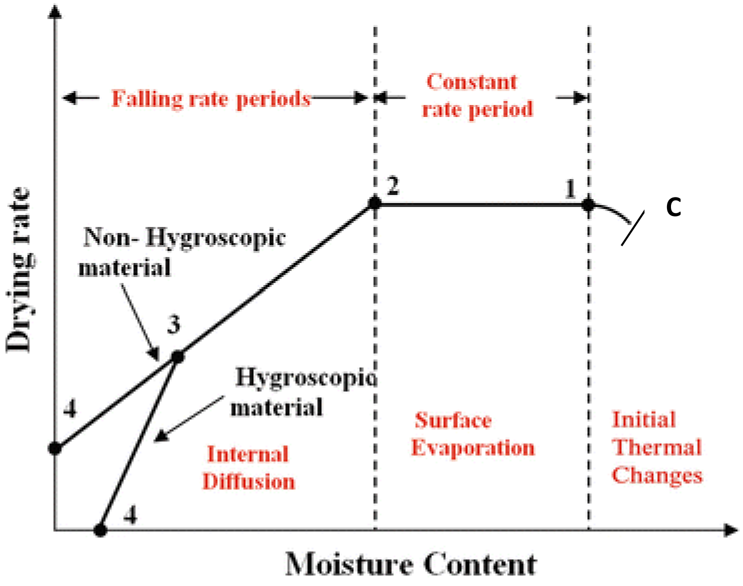


Figure 3: Typical drying rate curve Source: Vijayan *et al.* (2017)

This is the phase where the water acts as if the product is not present and the surface of the product is very wet and the water activity is one meaning the constant rate period continues as long as the amount of water evaporated is equal to the amount of water supplied to the surface of the material.

The next phase the product undergoes is the falling rate period and that starts from point 2 to 4. Typically it can be seen that the drying rate starts to decrease and the water activity falls to less than one. During this phase, all the surface water on the product evaporates continually until the surface is dried and the rate of drying is governed by the internal flow of liquid to the vapour state. There is a first falling rate from point 2 to 3 for hygroscopic materials. At point 2, the surface is completely dried. Heat required for moisture removal is transferred through the solid to the vaporization of moisture in the solid and the vapor moves out of the solid into the air stream. The amount of water removed during this phase is relatively minute compared to the constant rate and the first falling rate period. The second falling rate period (from point 3 to 4) is seemingly shorter because of the slow drying rate. However not all food products undergo such systematic phase of moisture removal. This consequence is a result of the fact that drying is influenced by the nature and property of the food, conditions of the drying air and the design of the dryer. Other environmental factors such as ambient temperature and humidity also play roles.

2.3 Solar Energy

Recent fluctuations of fuel prices have led to the consideration of solar energy as a good source of energy for the agricultural sector. The sun is the central energy producer in the solar system. It is in a shape of a ball and nuclear fission is continuously ongoing at its center. All natural cycles and processes such as rain, photosynthesis and ocean currents are driven by the solar radiation emitted from the sun. Solar energy therefore is a crucial part of life on earth. In spite of this, the incoming solar radiation energy in a year is 2×10^{17}kWh. The duration of the sunshine as well as its intensity is dependent on the time of the year, the weather conditions and also the geographical location. The solar radiation outside the atmosphere is nearly 1,360 W/m^2 (Tiwari, 2016) but when the solar radiation penetrates through the atmosphere, some of the radiation is lost and scattered from the different molecules in the atmosphere thus only 800 to 1000 W/m^2 can be obtained on ground level.

2.4 Solar Drying

Energy, the ability to do work is required in various forms. It is therefore necessary to explore and discover new sources and forms of energy, obtain sufficient supply of energy for future use and make it available wherever it is needed. Solar energy is a form of energy directly from the sun. The sun is the primary energy producer of our solar system. Only a small fraction of the tremendous amount of solar energy hits the earth (Tiwari, 2016). The solar surface temperature is 6000^{o}C which is equivalent to 70,000 to 80,000 kW/m^2 radiation intensity (Tiwari, 2016). Solar energy exists abundantly during the day and it is dependent on the cloudy or cloudless weather. Solar energy is the only continuously renewable source of energy that can be used for any practical purpose. Most importantly, it is the only totally non-polluting and inexhaustible energy source, especially in terms of drying process (Abubakar *et al.*, 2018).

Solar drying refers to a technique that utilizes incident solar radiation to convert it into thermal energy required for drying purposes. According to Li *et al.* (2011), solar drying was the modification of open sun drying technique which was used for most agricultural commodities. Solar dryers give faster drying rates by causing the air to move within the dryer to reduce the internal humidity (Oueslati *et al.,* 2012). The modern solar drying equipment uses optimum energy and time and occupies less area for producing better quality dried products with almost zero energy costs (Prakash and Kumar, 2013). Solar drying is often carried out at farm level right after harvest especially with highly perishable crops, at peak harvest time when local markets are saturated. Solar dryers are generally used for agricultural crop drying, fish and meat drying, dehydration of fruits and vegetables and in the dairy industries for the production of milk powder. It can also be used in the textile industries to dry textiles.

2.5 Review of Solar dryers

Over the past decades, solar dryers had been designed and constructed to address the challenges portrayed under the open sun drying; i.e. protection from dust, rain, debris, dews etc. However, solar dryers also have some drawbacks in their functioning and operations. Some of these setbacks are product overheating, undesirable product quality, limited drying space and capacity (Hii *et al.*, 2012).

For diversified use and improved functioning, Lutz *et al.,* (1987) set out to develop a multipurpose solar crop dryer comprised of a solar air heater and a tunnel dryer for drying various agricultural products. After a period of 3 years operation, he evaluated his solar dryer and discovered that the drying time and mass losses were reduced significantly. The energy required for the drying of 1000 kg of grapes was reported to vary from 11.2 to 23. 0 kWh depending on the climatic conditions and it cost 1 to 2 USD which was relatively cheaper. However the design was limited to the availability of electricity and its requirements therefore rendering a restricted and/ or limited usage.

Another example is a combined direct natural convection solar dryer with a simple biomass burner to dry fruits and vegetables in non-electrified location with a 20- 22 kg capacity of fresh pineapples, only 9% overall drying efficiency was reported when the pineapples were arranged in a single layer of 0.01 m thickness. Studies and research done by Shreekumar *et al.,* (2008) showed that the moisture contents of bitter gourd were reduced from 95% to 5% in a period of 6 hours after drying in their developed solar dryer against 11 hours for open sun drying. Such studies depict the need to tailor design a solar dryer to a particular type of product. It also shows how important the design of the dryer is to the drying of the product. To better improve the drying operation, while conserving the food quality and safety and minimizing post-harvest losses and drying periods, it is therefore crucial to look into either the redesign and improvement of the design.

2.6 The Greenhouse type Solar dryer

For better performance and drying efficiency of a solar dryer, the concept of the greenhouse effect can be inculcated into the design of a solar dryer. The Greenhouse type solar dryer operates based on the principle of the greenhouse effect. It allows incoming short wavelength solar radiations from the sun and traps the long wavelength solar radiations. Greenhouse dryers are used for crop cultivation, poultry, aquaculture and crop drying (Chauhan *et al.,* 2016). The greenhouse dryers often operate either in the natural convection (where a chimney or ventilator is provided for natural circulation of air entering inside the dryer) or forced convection mode (where an exhaust fan is provided for moving humid air outside the dryer). According to Pushpendra *et al.* (2018), a greenhouse solar dryer operating in the active mode is better as compared to the passive mode because atmospheric flow of air into the dryer helps in the moisture removal. Forced convective greenhouse solar dryers are used for foods with high moisture contents. In recent times, a lot of changes in design modifications have been provided to improve and enhance dryer performance and drying efficiencies. Each of these modifications are selected based on factors such as the type of food commodity and its moisture content, desired temperature for drying, demographic al location and installation of the dryer, climatic and weather conditions and the time for drying. Some of these modifications are

i. Thermal storage materials like sand, rock bed, black painted floors to increase temperature and reduce drying time. (Janjai *et al.,* 2007; Sevda and Rathore, 2010; Ayyappan *et al.*, 2016). This enables its usage during an off sun-shine period. Janjai *et al. (*2007) installed a polycarbonate sheet enveloped greenhouse solar dryer with floor area of 44 m^2 to dry fresh chilly peppers. An additional thermal storage solar panel was provided inside the solar dryer with a capacity of 53 W to bring the moisture content from 80% to 10%.

ii. Opaque northern wall to insulate and prevent heat loss to the surroundings and to improve the dryer's performance (Sevda and Rathore, 2010; Rathore and Panwar, 2010).

iii. PV integrated greenhouse solar dryer in the absence of electricity (Janjai *et al.*, 2007; Nayak and Tiwari, 2008; Ganguly *et al.,* 2010).

iv. Solar air heater to achieve faster drying (Chan *et al.*, 2018; Azaizia *et al.*, 2017).

v. Inclined and reflecting north wall to collect maximum radiations from the sun during the daytime (Sethi and Arora, 2009). The north wall inclination was performed to render support to drying trays with different width. It also aids the movement of heated air during forced or natural convection mode of solar drying.

2.7 Open Sun Drying

Reducing moisture content by ultimately drying is one of the safest and cheapest means of preserving foods which helps reduce postharvest losses in foods. In Ghana, open sun drying is commonly practiced where the food is either displayed or spread on surfaces to dry. Despite the potential of the open sun method to efficiently dry food commodities, there are some arguments concerning the safety and wholesomeness of the food product such as the slow drying process due to climatic variations, environmental contamination of the product and the extensive manual labor required (Fudholi *et al.*, 2010). Due to these challenges, more rapid, safe and controlled methods are needed. Most of the conventional techniques available which subject the drying process to high temperatures often render a decrease in quality of the dried product (Musa, 2012). These methods may introduce undesirable changes in appearance, flavor and aroma, colour and even cause modifications in the textural properties of the food. In Ghana, most of food products such as Koobi (salted dried tilapia), Kokonte (Cassava chips), Pepper, Cocoa beans, Coffee and some grains including corn, millet and sorghum are open sun dried.

2.7.1 Drying of Cassava Chips (Kokonte)

Value addition helps to increase the shelf life of food commodities like fresh cassava. Cassava drying is a traditional form of processing which do not require any in depth expertise. Prior to drying, the cassava is peeled, washed and cut into pieces. Fresh cassava roots are highly perishable and contains 65-70% moisture (Chavez *et al.*, 2010) thus it's plausible to subject it to drying so as to add value and to reduce postharvest losses. The cassava is cut into chunks and exposed in the open sun for a period up to two weeks to obtain an acceptable dry product (Dziedzoave *et al.*, 2003). In Ghana, dried cassava chips are milled into flour and is further used to prepare a delicacykokonte, which is eaten in some parts of Africa like Togo, Ghana and Nigeria. If the cassava chips are exposed to extreme temperatures during drying, it losses too much water and becomes dehydrated. If the temperature is too minimal, it allows microbial growth to take place and it is these factors that compromise the quality of the kokonte (Dziedzoave *et al.*, 2003).

2.7.2 Cassava flour properties and consumption on the Ghanaian market

The Brabender Amylograph cook paste viscosity provides a characterization of flours and further allow the evaluation of the product of the drying process. The Amylograph provides a reliable and reproducible picture of the enzyme (α-amylase) in flours and whole grains. The Amylograph operates by suspending flour into distilled water heated at constant heating rate of 1.5°C per minute within a rotating bowl. Depending on the viscosity of the suspension, a measuring sensor reaching into the bowl is deflected. This deflection is measured as viscosity over time i.e. against temperature and recorded on line. It is the shape of the curve (amylogram) plotted that provides additional information (Hadnađev *et al.*, 2011). There are six significant points on the curve;

i. Pasting Temperature: it denotes the initiation of paste formation which varies with starch type and modification and with additive present in the slurry.

ii. Peak Viscosity: it is cited irrespective of the temperature at which the peak is attained. Generally cooking must proceed through this stage to obtain a usable paste.

iii. Viscosity at 95°C: it reflects ease of cooking the starch

iv. Viscosity after 1 hour at 95°C: this indicates paste stability or lack thereof during cooking under relatively low shear.

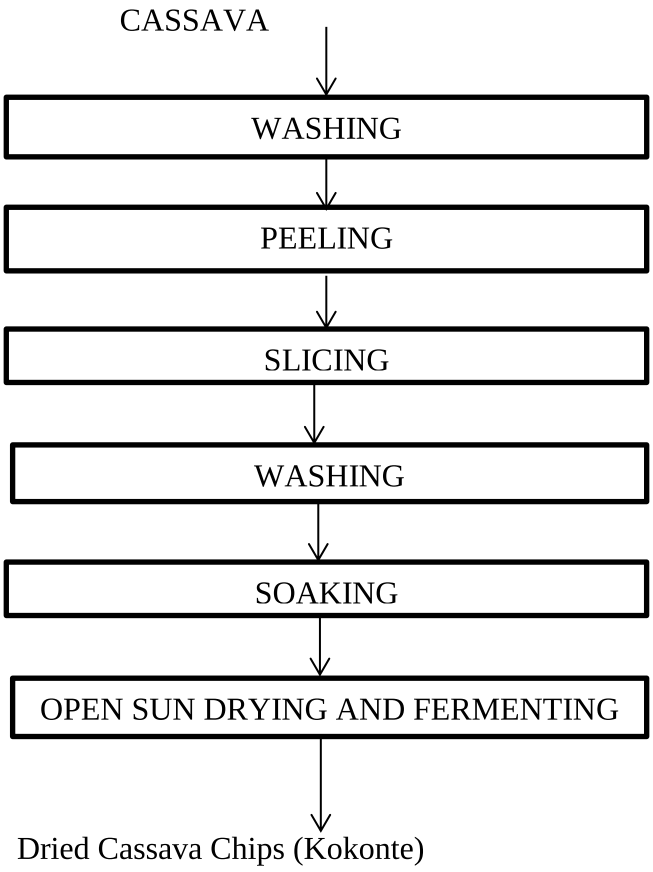
v. Viscosity at 50°C: this measures the setback that occurs on cooling the hot paste

vi. Viscosity after 1 hour at 50°C: this indicates stability of the cooked paste under simulated use conditions (Hadnađev *et al.*, 2011).

2.7.3 Challenges associated with the quality of OSD of cassava chips

According to Dziedzoave *et al.* (2003), the period of drying of the cassava chips has an influence on the final colour and particle size distribution. They further explain that, the colour is equally affected by microbial (specifically molds) contamination. At the cassava economic market, good product quality includes its colour, particle size distribution, pasting characteristics and final moisture content. Drying plays a major role in the final quality of the cassava flour. Due to inconsistencies in the weather conditions, the processing of cassava into kokonte is challenged and as such cannot be an all year round affair. Some of the challenges are insect infestation, bird droppings and dust contamination.

2.7.4 Flow Diagram for the Production of *Kokonte*

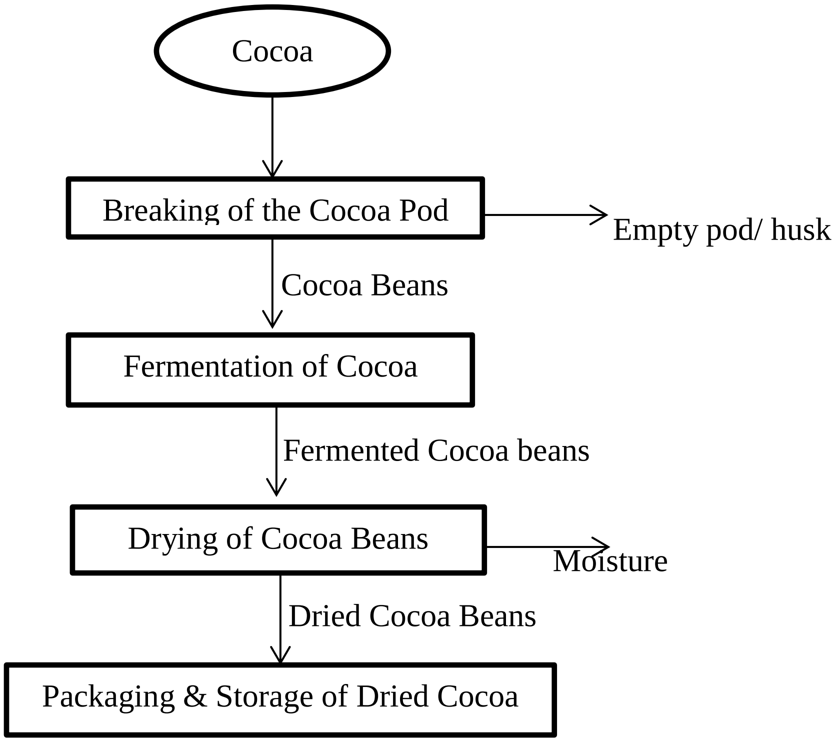


2.7.5 Cocoa Preparation for Processing

Before cocoa beans can be processed into chocolate the harvested cocoa pod is cut open and the seeds removed (beans). This is followed with fermentation of the mucilaginous beans and finally the drying of the beans to a moisture content of about 6 % -7.5 % (Afoakwa, 2014). The dried beans are then bagged and stored for latter or immediate use.

The two most important unit of operations during the preparation of cocoa beans for processing are the fermentation stage and the drying stage. It is at these two stages where the distinct quality attributes of the cocoa beans are developed. Alternatively if these processes are not done properly, the quality of the beans will be compromised.

Figure 4: Flow diagram for cocoa preparation for chocolate processing



2.7.6 Fermentation of Cocoa Beans

Cocoa beans fermentation involves insulating the wet mass cocoa beans. The primary objective of fermentation is to develop flavor and aroma in the beans. It has been identified that fermentation is the initial step required in the development of the flavor precursors (Afoakwa, 2014). In the fermentation process, the beans pulp is removed and the sugar is converted to acetic acid by the acetic acid bacteria which oxidizes the ethanol produced from the sugar. There is microbial succession of a wide range of yeasts and lactic-acid bacteria. Fermented cocoa beans generally have moisture content between 55 % and 60 % (Thompson *et al.*, 2007).

Fermentation can be conducted in a number of ways such as in a box, in a heap covered with banana leaves and in baskets. Both the baskets and the box will equally have to be covered with banana leaves at all sides and bottom. Furthermore in all three ways of fermentation, perforations will have to be made with a knife through the banana leaves to allow the mucilaginous liquid from the pulp to drain out. Insufficient drainage of the liquid from the pulp will result in a bad fermentation which will affect the final quality of the beans. The upper layer of fermenting cocoa must also be covered with banana leaves or jute bags. This controls air penetration into the fermenting cocoa and reduces unnecessary lost moisture. Uncontrolled moisture lost would affect the efficient fermentation of the cocoa and cause the polyphenol compounds degradation which can lead to an increase in Nitrogen Ammonium production leading to undesirable flavours.

An additional reason for lining the baskets and boxes and covering the fermenting cocoa is to prevent the loss of heat by dissipation during the fermentation. This would cause the cocoa to attain the high temperatures required for a good fermentation. Preferably farmers and cocoa processors are advised to either use banana leaves or jute bags to cover the fermenting beans or a combination of the two to conserve ore heat. Fermentation lasts between 4 and 7 days.

Fermenting temperatures for the cocoa beans range between 45^{o}C and 50^{o}C (Guehi *et al.,* 2010). On the second day of fermentation, the beans are turned either with the hands or shovel to introduce air into the beans and also to make fermentation even in the beans. The rate of fermentation increases after two hours when air gets into the beans and this helps improve the flavor and aroma. However if the temperatures are lower than the expected range, the farmer is advised to turn the beans every day of the fermentation period till the fermentation is completed. This is because consistent turning of the beans increases the temperature which directly improves the fermentation.

In a situation of slow fermentation, an increase the number of turn overs can be introduced by the farmer to cause a rise in temperature which will aid proper fermentation. The fermentation temperature at all sides of the cocoa bean mass must be relatively uniform to ensure the final bean quality. Unfermented beans have a slaty appearance and poorly fermented beans have a purple appearance. The fermentation stage of cocoa beans is also identified as the flavor developing stage.

2.7.7 Drying of Cocoa Beans

A major step in the preparation of cocoa beans for processing is drying after fermentation. The drying process in addition to reducing the moisture content of the beans also completes the chemical reactions (oxidation) that started during the fermentation process and develops the chocolate brown colour (Lasisi, 2014). Properly dried beans are usually 6 % - 8 % moisture content (wet basis) and have a relatively reduced acidity. There are several methods adopted for drying cocoa beans but usually the beans are open sun dried and mechanically dried. Generally the open sun method is the method adopted in Ghana for the drying purposes due to socio- economic conditions, climatic conditions and demographical location. According to Takrama and Adomako (1996), using ambient air for slow drying of cocoa beans have produced a good bean quality but issues of over fermentation due to inadequate air and heat flow have been reported. Drying plays an important role in the flavor development, bean acidity and moldiness (Jinap *et al.*, 1994). The drying of cocoa in the humid regions is coupled with relatively high humidity also resulting in slow drying process. In Ghana, cocoa beans are ultimately dried by farmers before selling them out to their substantive buyers. These farmers mostly employ open sun drying mechanism. Open sun drying is carried out by spreading the beans on mats raised off the ground or on concrete floors during the period of sunshine. The farmers spread out the beans on raffia woven wooden mats that are raised off the ground level with the aid of wooden pegs or stands. The beans are spread out in the early mornings when the sun rises. Periodically, the beans are spread apart and or turned over with the hands or a rake to ensure consistent and effective moisture removal. The beans are collected before sunset or before the occurrence of rain. They are collected into jute sacs and kept in barns till the next day when the drying continues. After 7 days, with a fair weather during the period of drying the beans are expected to be dried. Beans dried on ground level are easily contaminated by insects or domestic animals and they tend to become dusty. The cocoa bean drying combines the heat and mass transfer concept; the moisture exists on both on the surface of the bean and inside the bean. In the absence of excessive rainfalls and presence of sufficiently high amounts of sunshine, open sun drying is effective in drying the beans. Open sun drying is dependent on the weather conditions. During the dry season, drying may last for 7 days but 30 days during the wet season (Jain and Tiwari, 2003).

2.7.8 Challenges associated with the quality of OSD of cocoa beans

Open sun drying is a simple and inexpensive way of drying cocoa beans due to the availability of sunshine. Efficient drying influences market quality, the development of flavor, final bean acidity and moldiness. Any adverse change in climatic condition can affect the drying process thus the final cocoa bean quality. Due to the uncertainties in the weather, open sun drying may lead to a slow rate resulting in moldiness and the development of off flavors (International Cocoa Organization, 2009). In the humid tropics, prolonged drying also leads to microbial growth affecting the final quality. The cocoa beans are more likely to be adulterated with dust and other debris. Long periods of drying can contribute to post harvest losses if the dried beans turn out to be of poor quality. These factors affect the final bean quality and their respective corresponding end products. Furthermore, the cocoa pulp is sterile prior to breaking and fermentation but once the pod is cracked open and the beans are removed, the pulp is inoculated with microbes from the environment (Takrama & Adomako, 1996; Afoakwa *et al.*, 2010). Spore forming Bacillus specie become dominant and these form undesirable fatty acids that renders the beans with off flavors and this affects the final bean quality. Efficient drying is then deemed responsible for eliminating and inhibiting these microbial reactions but if drying is inefficient, interrupted and stopped can contribute to poor bean quality (Nielson *et al.*, 2007).

2.7.9 Challenges associated with the quality of mechanical drying of Cocoa

Artificially dried cocoa beans are of inferior quality on the world market. Employing artificial dryers in the drying of the beans make the beans more brittle and yields a more cracked or broken bean. Also due to the fact that these dryers operate within temperatures of 60^{o}C – 90^{o}C to ultimately dry the beans to the accepted moisture content, enzymes responsible for the development of chocolate flavor are often destroyed (Jinap *et al.*, 1994). This high temperature causes rapid drying of the testa thereby hardening and preventing the outward migration of acetic acid from the cocoa bean (Jinap *et al.*, 1994). Artificial drying of cocoa beans can also be seen as economically costly due to the use of electricity.

2.8 Mathematical Modelling

A mathematical model is a description of a system using mathematical concepts and language. Mathematical models describe our beliefs about how the world functions. A model may help to explain a system and to study the effects of different components and to make predictions about an occurrence. These models are used to further provide insights, answers and guidelines useful for the originating application (Neumaier, 2004). Mathematical models are employed in various disciplines such as physics, social science, biology, engineering, architecture, etc. In modelling mathematically, there are two basic factors to consider in order achieving the set objective; the state of the knowledge about a system and how well modelling is performed. To be able to develop a scientific understanding regarding the model, repetitive quantitative expression of current knowledge concerning the problem should be done and there should be a test on the effect of changes in a system.

2.8.1 Classification of Models

According to Marion and Lawson (2008), the first category for the classification of models is based on the type of outcome they predict. Based on this there are two main classification of models; Deterministic and Stochastic models. Deterministic models ignore random variation and always predict the same outcome from a given starting point. Stochastic models employ a more statistical approach and predict the distribution of possible outcomes. The second category of classification of models is based on the types of models to consider and the level of understanding. Empirical and mechanistic models are examples. In empirical models, no account is taken with regards to the mechanism by which changes occur. It merely identifies that changes do occur and explains quantitatively how the changes occur under different conditions. Mechanistic models on the other hand use tons of theoretical information to describe what happens at one level in the hierarchy by considering processes at lower levels. The third category of classification lies between the two categories mentioned afore. This classification is complementary to the two types (mechanistic and empirical).

2.8.2 Advantages of Mathematical Modelling

i. It gives precision and direction for problem solution

ii. It allows the efficient use of modern computing skills and capabilities

iii. It also prepares the way for better design or control of a system

iv. Mathematical models have a proven record of success in further applications

v. It ensures a thorough understanding of a system using the appropriate model

2.8.3 Henderson Pabis and Logarithmic Models

The Henderson Pabis and Logarithmic models are examples of the complementary classification of models. These two offer a theoretical background and ease of application. These two models are among the few models that are used for thin layer drying of agricultural produce (Kashaninejad *et al.*, 2007). The Henderson and Pabis model were derived through the general series solution of Ficks' second law and has produced good correlations in predicting the drying of corn. The Henderson and Pabis model can be written as

$$MR = \frac{M - M_e}{M_O - M_e} = a\exp(-kt)$$

Where a, k are constants and t is drying time, MR is moisture ratio, M_o= initial moisture prior to drying, M_e= expected moisture content and M is the final moisture content after drying. The Logarithmic model was also successfully used to describe drying characteristics of apricots (Togrul and Pehlivan, 2002) and pumpkin slices (Doymaz, 2007). It can also be written as

$$MR = \frac{M - M_e}{M_O - M_e} = a\exp(-kt) + c$$

Where a, k are constants and t is drying time, MR is moisture ratio, M_o= initial moisture prior to drying, M_e= expected moisture content and M is the final moisture content after drying. It can clearly be seen that the Logarithmic model is a modification of the Henderson and Pabis model by adding a constant c. Both models take into consideration the simultaneous heat and mass transfer (internal and external) and predict the temperature and the moisture gradient in the product (Erbay and Icier, 2009) and such a peculiarity best suits the modelling of drying.

CHAPTER THREE

3.0 MATERIALS AND METHODS

This study was carried out in three parts. Firstly, the design and construction of the green house type solar dryer. Secondly, the drying of a) cassava slices and chunks and b) cocoa beans. Third component involved laboratory analysis of dried samples and mathematical modelling.

3.1 Design and Construction of Greenhouse Type Solar Dryer

The overall design of the solar dryer mimics the design of a greenhouse that is used for cultivating seedlings for agricultural purposes. The design of the greenhouse solar dryer also includes the concept of a walk-in dryer that provides shelter from the rains and dust contamination. There were four inlet/outlets with two positioned at each side to aid in the airflow into and out of the dryer to enhance moisture removal and heat reduction within the dryer. All four inlets/outlets had a netting screen to prevent the entry of insects and other foreign matter. The air inlets/outlets had flaps overlapping them. These flaps were inclined at angles of 15^o, 30^o, 45^o, 60^o, 90^o periodically with wooden battens depending on the intensities of heat generated inside the solar dryer and moisture content of the food product being dried. The heat energy generated inside the dryer was dependent on the time of the day, atmospheric relative humidity and temperature.

The empty greenhouse type solar dryer was monitored for a period of two weeks during which temperature and relative humidity were measured and the fluctuations in temperature and relative humidity recorded. During the first week, temperature and relative humidity measurements were taken at 6 a.m. in the morning and 6 p.m. in the evening. During the second week, temperature and relative humidity measurements were taken at a 3 hour interval starting from 6 a.m. in the morning till 6pm in the evening. A digital thermo-hygrometer with dew point and wet bulb (Cole Palmer, Model 90080-03, USA) was used in measuring both temperature and relative humidity. The

Greenhouse type solar dryer was designed with a total surface area and volume of 35.7743 m^2 and 20.3345 m^3 respectively.

3.1.1 Material Selection

The materials were selected based on the ability to raise the temperature inside the dryer through the radiation of solar energy and the potential to trap the heat inside the dryer to be used for drying purposes. Another factor considered was on the local availability of the materials. The materials selected and used for the construction were:

i. Wood (*Duahoma*, a cheap, durable and insect resistant local type of wood) with specifications; $2in \times 4in \times 14ft;\ 2in \times 3in \times 14ft;\ 1in \times 12in \times 14ft$

ii. Battens

iii. Nails

iv. Hasp and Staples

v. Hinges

vi. Polyethylene (0.125mm) used as the cover and solar energy collector

vii. Screen Nettings

Wooden battens were used for fastening the polyethylene sheet unto the wooden frame. Nettings with a mesh size of 300 µm were used to cover the inlet and outlet windows to prevent the entry of insects. A raised platform with a wooden mat was used to spread the food during drying. A similar wooden platform and mat were provided in the open air for the open sun drying purposes. The design of the solar dryer was based on the principle underlying greenhouse effect (i.e. the trapping of the sun's heat in earth's lower atmosphere due to the greater transparency of the atmosphere to visible radiation from the sun). The design of the greenhouse type solar dryer was in two sections; the roof (triangular) and a base (rectangular) as shown.

Illustration 1. The Greenhouse type solar dryer

3.1.2 Design Calculations of the Greenhouse type solar dryer

$\underline{\boldsymbol{Total\ Volume\ covered\ by\ the\ Greenhouse\ Type\ Solar\ Dryer, V}}$

The total volume of the greenhouse type solar dryer encompasses the total space available for air and heat to occupy. Below is the total volume calculation.

$$V = (volume\ of\ Triangular\ section, v_T + Volume\ of\ Rectangular\ base, v_R)$$

$$volume\ of\ Triangular\ section, v_T = (\tfrac{1}{2} \times b \times h) \times \mathrm{L}$$

$where\ b = breadth, \mathrm{h} = \mathrm{height}, \mathrm{L} = \mathrm{length}$

$$v_T = \frac{1}{2} \times 253.3cm \times 63cm\ ) \times 313.1cm$$

$$= 2497222.98cm^3$$

$$Volume\ of\ Rectangular\ base, v_R = L \times b \times h$$

$$= 253.2cm \times 313.1cm \times 225cm$$

$$= 17837307cm^3$$

$$\therefore\ V = 2497222.98cm^3 + 17837307cm^3$$

$$= 20334529.9cm^3 \quad \approx \mathbf{20.3345m^3}$$

$\underline{\boldsymbol{Total\ Surface\ Area, A_s}}$

The total surface area of the greenhouse type solar dryer refers to the land space covered from the roof to the ground level and the spaces covered by the sides, front and back boundaries. The design of the dryer was divided into two sections; the triangular prism roof and the rectangular base. Each section's area was calculated separately and added together to obtain the total area of the dryer. Below is the total surface area calculation.

$$A_s = Area\ of\ Triangualr\ Prism, A_p + Area\ of\ Rectangular\ cuboid\ base, A_c$$

$$Area\ of\ Prism, A_p = L + 2B$$

$$where\ L = Lateral\ side\ or\ sum\ of\ the\ area\ of\ all\ rectangular\ sides$$

$$B = Base\ area\ (i.e.area\ of\ one\ triangular\ base)$$

$$L = (253.2cm \times 313.1cm) + (137.5cm \times 313.1cm) + (313.1cm \times 137.5cm)$$

$$= 165379.42cm^2$$

$$B = \frac{1}{2} \times b \times h$$

$$= \frac{1}{2} \times 253.2cm \times 63cm$$

$$= 7975.8cm^2$$

$$\therefore\ A_p = 165379.42cm^2 + 7975.8cm^2$$

$$= 173355.22cm^2$$

$$Area\ of\ Rectangular\ cuboid\ base, A_c = 2(hw + wh + hl)$$

$$= 2[(313.1cm \times 225cm) + (253.2cm \times 225cm) + (225cm \times 253.2cm)]$$

$$= 184387.5cm^2$$

$$Therefore\ Total\ Surface\ Area, A_s = 173355.22cm^2 + 184387.5cm^2\ \approx \mathbf{35.774272m^2}$$

3.1.3 Drawings of the Greenhouse type Solar dryer

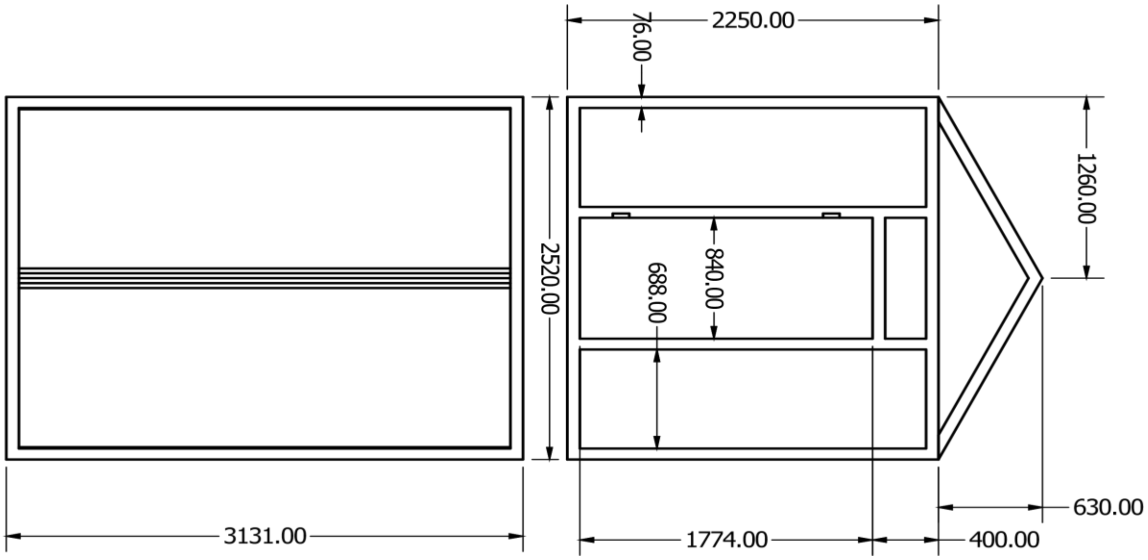


Illustration 2. Floor space (left) and Front View (right)

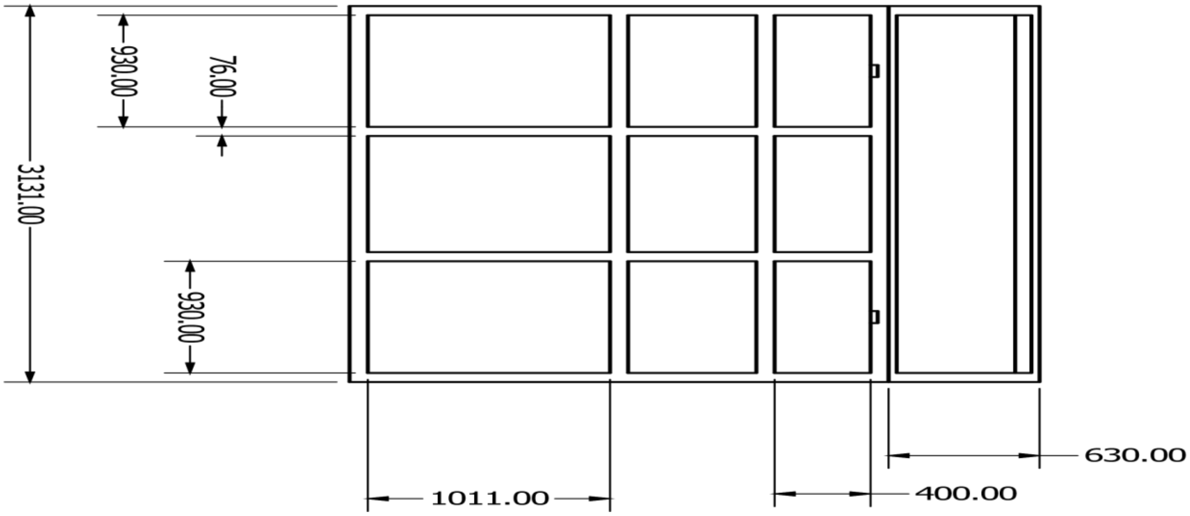


Illustration 3. Side View of GTSD

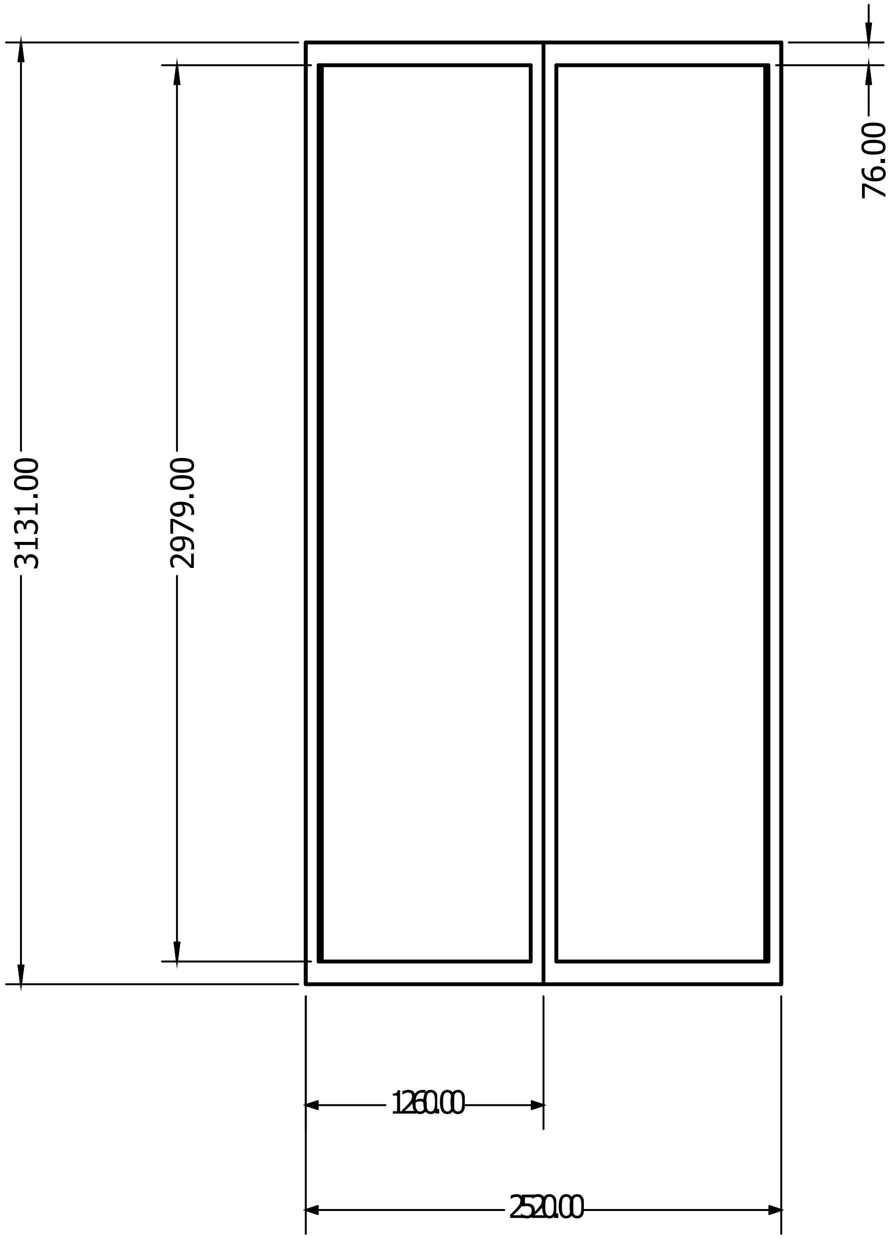


Illustration 4. Top View of GTSD

3.1.4 Construction and finishing stages of the Greenhouse type solar dryer

Illustration 5. Base Framework of GTSD

Illustration 6. Base and roof framework of GTSD

Illustration 7. Completed framework with door of GTSD

Illustration 8. Completed GTSD with polyethylene cover

3.2 Cassava

3.2.1 Source of cassava sample

Matured cassava (*Bankyehemaa* variety) was obtained from a farm situated at the University of Ghana main campus. The cassava was harvested using a mattock in the morning when the ambient temperature recorded was 25^0C and transported to the processing laboratory of the Department of Nutrition and Food Science, University of Ghana.

3.2.2 Cassava Sample preparation

The weighed tubers of cassava were manually peeled and washed. Eighteen kilograms of peeled cassava flesh was divided into two, half was sliced into 0.47 cm slices using a Qualheim Electro-cut Vegetable Cutter and Slicer (model number 101, USA). The other half was prepared as chunks by cutting with a kitchen knife into uniform sizes of 4 cm length, 2 cm breadth and 1.5 cm height.

3.2.3 Cassava drying

The cassava slices and the chunks were further divided into two equal parts before being subjected to the two drying methods. Thus 4.5 kg each of cassava slices and chunks were dried under the two methods of drying (open sun and solar drying). Before the drying, moisture content of the cassava was determined using the AOAC, 2005; Method 930.15 for moisture determination. The drying of the cassava chunks and slices was repeated thrice to achieve a better assessment and evaluation of the drying process coupled with the design of the solar dryer and the impact on the final quality of the food products.

3.2.4 Solar drying of Cassava

Samples of cassava slices and chunks (4.5 kg each) were dried in the green house type solar dryer. The cassava samples were evenly spread on the wooden mat. Drying started from 6 a.m. in the morning and ended at 6 p.m. each day. All four outlets/inlets were inclined at an angle of 45^O. Temperature and relative humidity variations in the dryer were monitored each day with readings recorded at intervals of 15 minutes (i.e. to enable an average temperature and humidity to be calculated) during sample collection. At 6 p.m. each day, the inlet and outlet windows were shut by removing the battens used to incline the window flap at the 45^0 angle to prevent the escape of heat from inside of the dryer and the entry of moist air from outside of the dryer during the night and dawn.

3.2.5 Open sun drying of Cassava

Drying started at 6 a.m. and ended at 6 p.m. each day. Samples of cassava slices and chunks (4.5 kg each) were evenly spread out on a wooden mat in the open sun and allowed to dry. The ambient atmospheric temperature and relative humidity were monitored and recorded each day during sample collection until drying was completed. At 6 p.m., the cassava samples were covered with a polyethylene sheet which was then secured with brick stones to prevent it from flying away during strong winds at night and also to render some protection from rain and dew.

Illustration 9. Open sun drying of cassava slices and chunks

Illustration 10. Solar drying of Cassava slices and chunks

3.3 Cocoa

3.3.1 Source of Cocoa sample

Matured and ripened Forastero variety of cocoa was sourced from a recognized cocoa farm which is situated in the Eastern Region of Ghana and used for this study. The cocoa pods were transported in jute sacs from the farm to the laboratory on the University of Ghana campus.

3.3.2 Sample preparation of Cocoa

Upon arrival in the laboratory, the cocoa pods were first weighed to determine the average weight of a cocoa pod and beans. The cocoa pods were then broken to release the beans for the fermentation process. The beans were fermented using the basket method where the cocoa beans were placed in a wooden basket lined and covered with banana leaves. The initial fermentation temperatures of the room and the heaped beans were 27^{o}C. A Cole Parmer thermocouple thermometer dual type JKTE temperature probe was inserted into the heap of the bulk fermenting beans and temperature was monitored until fermentation was completed. Fermentation lasted for a maximum of 7 days. As fermentation proceeded, a thick liquid seeped out. The change in pH of this exudate was monitored during the fermentation period. The cocoa beans were weighed just after fermentation and the moisture content of the beans were determined prior to subjecting the beans to the drying methods.

3.3.3 Drying of cocoa beans

Fermentation of the cocoa beans yielded 18 kg of the beans which were prepared for drying. The beans were divided into two equal halves (i.e. 9 kg each) and dried in the open sun or greenhouse type solar dryer.

3.3.4 Solar Drying of Cocoa beans

Cocoa beans (9 kg) were evenly spread on a wooden mat placed inside the solar dryer and left to dry. The maximum and minimum drying temperatures and humidity of the solar dryer were monitored each day until drying was complete. The cocoa beans were gently stirred twice daily by running clean hands through the beans to separate beans that are stuck together and also to evenly turn over the beans to ensure consistent drying. Samples were collected each day at 6 a.m. and 6 p.m. to determine amount of moisture until a moisture content of about 6 - 7.5% was achieved after which percentage free fatty acid content, bean cut test and total plate count analysis were determined to ascertain the quality of the cocoa beans. The cocoa drying was repeated twice to enable proper evaluation of the impact of the design of the dryer and its corresponding drying effect on the final product quality.

3.3.5 Open Sun Drying (OSD) of Cocoa beans

Cocoa beans (9 kg) were evenly spread on a wooden mat placed on a wooden platform in the open air and left to dry. The cocoa beans were stirred with the clean hands to ensure even drying was achieved and to separate the beans that were stuck together. Samples were collected to determine moisture content until 6 - 7.5% moisture content was achieved. Drying was terminated after this moisture content was achieved. Samples of the beans were then taken for the determination of moisture, free fatty acid and bean cut test.

Illustration 11. Basket fermentation of Cocoa beans

Illustration 12. Open sun drying of Cocoa beans

Illustration 13. Solar drying of Cocoa beans

3.4 Laboratory analysis

All laboratory analyses were performed in triplicates to aid correct data analysis and statistical interpretation.

3.4.1 Moisture determination

Two grams (2 g) of the dried cocoa beans and cassava cocoa samples were weighed in triplicates and dried at 105 °C for 18 hours in a Cole Parmer stable temperature oven (model specification; 1.5 cu ft, 120 VAC and manufactured in the USA) to a constant weight. Samples were removed, cooled in a desiccator and weighed. The moisture content was calculated and expressed as a percentage of the mass of sample taken (AOAC 2005; 972.20).

3.4.2 Drying rate determination

Drying rate can be calculated on the basis of the initial moisture content and the corresponding final moisture content after drying for a specified time by using the relationship below;

$$\frac{dw}{dt} = \frac{w\,(X_o - X_f)}{t}$$

Where w= amount of dry material in the food

X_o= initial moisture content of the food

X_f= final moisture content of the food

$$\frac{dw}{dt} = drying\ rate$$

3.4.3 Milling

Dried slices and chunks of cassava from both the solar dryer and the open sun drying were milled using a hammer mill and then sieved using a 150 micron sieve. The resultant flour was packaged into zip lock plastic bags and stored in the lab at a room temperature.

3.4.4 Water Activity

The water activity of the flour samples was determined using the Rotronic HP23-AW-A-SET-14. This device measures the temperature and humidity of the sample and calculates the water activity. The water activity was performed for each sample in triplicate to ascertain accuracy. The flour was put into a plastic sample dish which was then placed into the sample holder. The measurement probe was then placed on top of the sample holder which is connected to the handheld instrument that displays the water activity and the temperature.

3.4.5 Particle size distribution

According to Sonaye *et al.* (2012), approximately 100 g of dried and milled cassava samples (flour) were measured and poured into a column of sieves with the largest screen size of 1.25 mm and 100 µm as the smallest size. The sieves were arranged in a descending order of size from the top with a receiver at the base. The column was placed in a Test Sieve Shaker with model number A060-01 and shaken for 20 minutes. After the shaking was complete the residual material on each sieve was weighed. The weight of the sample on each sieve was then divided by the total weight of the sample (i.e. 100 g dried cassava sample) to give a percentage retained on each sieve. To obtain the percent of aggregate passing through each sieve, the percent retained on each sieve was first calculated using the following equation

$$\% \text{ Retained} = \frac{W_{sieve}}{W_{total}} \times 100\%$$

Where W_{Sieve} is the weight of aggregate on the sieve

W_{Total} is the total weight of the sample.

3.4.6 Colour determination of dried Cassava flour samples

The colour of the cassava flour was measured using a Konica Minolta Optics colourimeter (model number CR-410) manufactured in the USA. The dried cassava flour samples were weighed into a petri dish and covered with another petri dish. The handheld colourimeter was gently positioned over the flour samples in the petri dish and a white light shone onto the sample to obtain the colour of the three layers (bottom layer, middle layer and top layer). The colour coordinates were recorded as: L*= lightness (0=black, 100=white), a*= (-a*=greenness, +a*= redness), b*= (-b*=blueness, +b*=yellowness).

3.4.7 Flour pasting property

Using the Amylograph-E (Model 800150, 230V, 50Hz, C. W. Brabender Instruments, Inc. 50 E. Wesley St South Hackensack, NJ 07606, USA) the pasting characteristic and viscosity of the resultant flour from the dried cassava chunks and slices were determined. The dried cassava chips were milled using the Christy and Norris Essex Major Hammer mill sieve size of 5 mm (model number; N10857 United Kingdom). The resulting flour was weighed at 40 g on a dry weight basis and dissolved in 24 0 ml of distilled water and poured into the sample bowl of the amylograph. The amylograph was run at 75 rpm using 700cmg sensitivity cartridge. For all samples, the temperature at which measurement were started was 50^{o}C and the sample was heated and cooled at a rate of 3^{o}C per minute. Sample upon reaching 92^{o}C was held at this temperature for 15 minutes and then cooled to 55^{o}C and held at this temperature for a further 15 minutes. The critical parameters from the Amylograph were; gelling temperature, peak viscosity (BU), Viscosity at 92^{o}C (BU), Viscosity at 92^{o}C after holding, Viscosity at 55^{o}C and viscosity at 55^{o}C after holding. Other parameters measured are breakdown viscosity and setback viscosity.

3.4.8 Roasting of cocoa beans

Approximately 500 g each of the solar dried and open sun dried cocoa beans were roasted in a Memmert UF 75 Roaster set at a standard temperature of 125^{0}C for 45 mins (AOAC, 2000).

3.4.9 De-shelling of cocoa beans

After roasting, the cocoa beans were manually de-shelled using a knife to scrape off the shells to obtain the cocoa nib.

3.4.10 Free Fatty Acid (FFA)

Fat from the samples was extracted with petroleum ether (40–60^{o}C) using the Soxhlet extraction method (AOAC, 2005 method 963.15). Free fatty acids of the oils extracted was analyzed using the International office of cocoa, chocolate and sugar confectionery; (IOCCC, 1996) method 42-1993. Approximately 5 g of the cocoa fat (W) that was extracted by the Soxhlet method was weighed into a dry 250 ml stoppered conical flask and 25 ml of 95 % ethanol/ether (1:1) and phenolphthalein indicator were added. The solution was then titrated with 0.1N NaOH, (V) and shook constantly until a pink colour persisted for 30 seconds and the percentage FFA (% oleic acid) was calculated as follows:

$$FFA\ (\%\ Oleic\ acid) = \frac{(28.2 \times Volume\ of\ NaOH\ used \times Normality\ of\ NaOH\ used)}{Weight\ of\ sample}$$

3.4.11 Bean cut test

One of the methods for cocoa bean quality assessment is the bean cut test. This test was performed to determine the level of fermentation and its effect on the beans during drying. In accordance with the ISO 1114:1977 method, 300 beans each from the two drying methods were selected and cut lengthwise through the middle, so as to expose the maximum cut surface of cotyledons. Both halves of each bean were visually examined in full daylight or equivalent artificial light to identify and sort out defectives. Beans with each defective type of bean (using the bean cut test chart as a reference) were counted separately and the result for each kind of defect was expressed as a percentage of the 300 beans examined. Defective beans include slaty, insect damaged, flat beans, over-fermented and moldy beans. According to international standards, moldy beans, slaty beans, insects damaged and germinated or flat beans should each not exceed 3% by count. Using the bean cut test chart below, the quality of the 300 cocoa beans selected from the two drying methods were assessed.

Source: Cocoa & Chocolate Manual (2009) - ADM

Illustration 14. Cut test chart for determining cocoa bean quality

3.5 Statistical Analysis

Statgraphics software version 3.0 (STSC, Inc., Rockville, MD, USA) was used to analyze the data (moisture content, drying rate and baseline temperature and relative humidity). All laboratory analysis were done in triplicates and expressed as Means ± SD. Analysis of Variance (ANOVA) was done to determine the effects of drying time, drying method and dryer type on some critical parameters.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSIONS

4.1 Design, construction and evaluation of the Greenhouse solar dryer

4.1.1 Design Characteristics

The Greenhouse type solar dryer designed had the following characteristics:

i. A greenhouse type solar dryer had a total volume of 20.3345 m^3 and a total surface area of 35.7742 m^2.

ii. It was constructed with readily available local materials that are available in all agricultural communities.

iii. Had a wooden framework which ensured stability for the dryer during strong winds.

iv. The polyethylene cover ensured the penetration of radiations from the sun into the dryer.

v. The netted four window outlets placed on the top ensured the movement of air, exit of heated air and moisture and prevented entry by insects.

vi. A raised wooden platform was introduced to act as the drying platform.

vii. The lockable door of the dryer provided security from theft and other mammals.

4.1.2 Temperature and Relative humidity of the empty Greenhouse solar dryer and Open Sun drying

Baseline data on temperature and relative humidity attained in the dryer were monitored for 14 days. The data obtained is summarized in Appendix 1 and Figures 4 to 9. For the 12-hour period monitored, variations in temperature and humidity were found. The peak temperatures for most days were found to be at 12:00 and 13:00 hours GMT (Figures 4, 5 and 6). Generally the temperatures were relatively higher for the Greenhouse type solar dryer compared with the Open sun drying (Figures 4, 5 and 6). These results give indication that the Greenhouse type solar dryer potentially will provide the environment higher heat and possibly higher rate of drying. Both drying systems use heat energy trapped from the sun but it can be deduced that the temperature gradients between GTSD and OSD are different. While GTSD total volume and surface are confined to 20.3345 m^3 and 35.7742 m^2 respectively, the OSD's total surface area and volume are open to the ambient atmosphere. This signifies that the design, design material and enclosed space inside the GTSD offers the potential of the drastic buildup of heat energy resulting in the higher temperatures recorded.

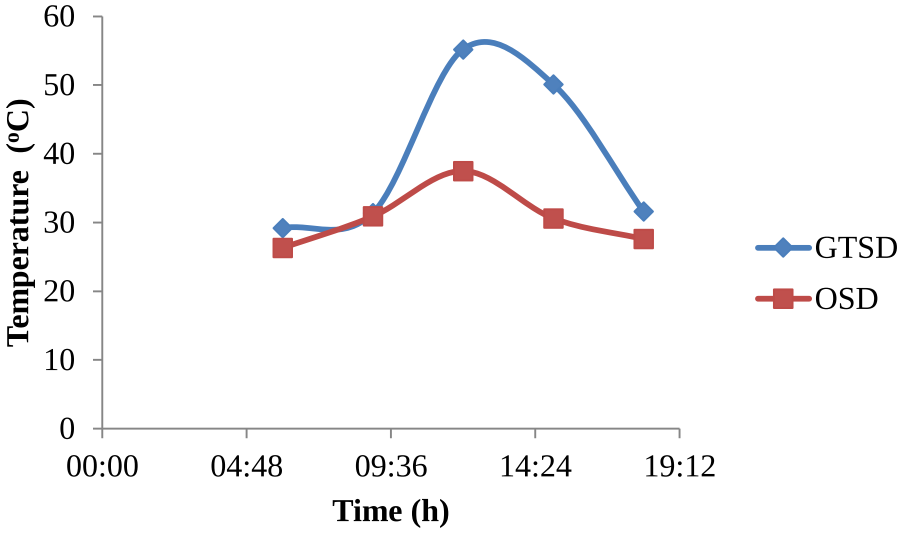


Figure 5. Day 1 Baseline Temperature for GTSD and OSD

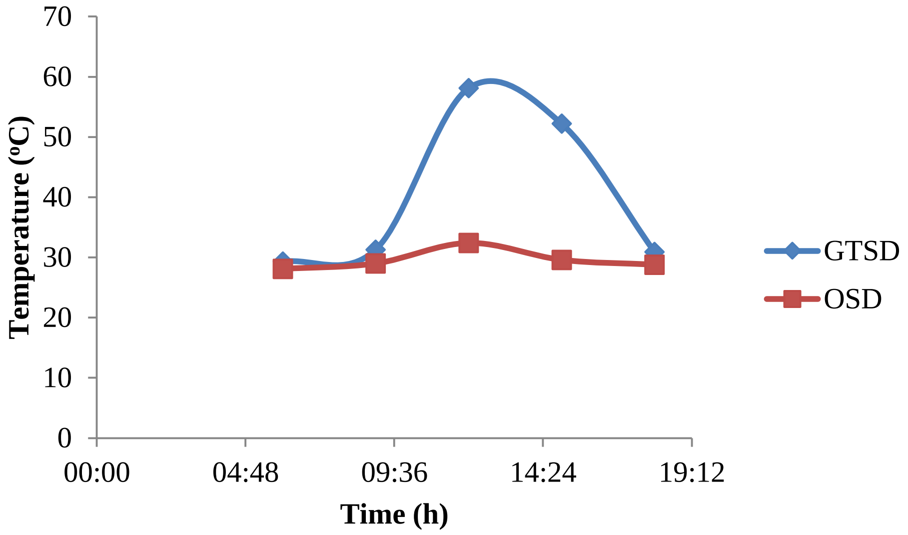


Figure 6. Day 7 Baseline temperature for GTSD and OSD

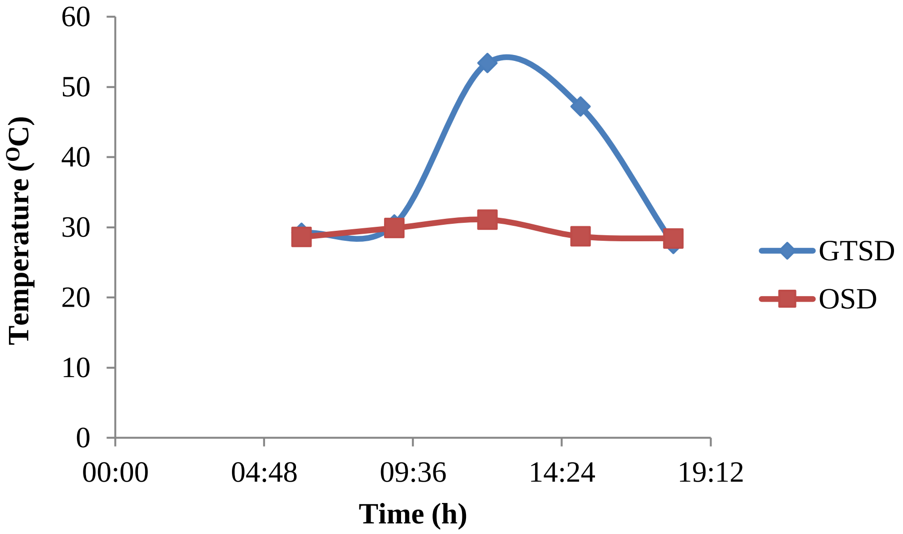


Figure 7. Day 14 Baseline Temperature for GTSD and OSD

Analysis of variance on the data delineating Time of day, Dryer type and Drying days revealed that the temperature measured was significantly influenced by the drying method and the time of day (Table 1). This means that the temperature attained is dependent on the method of drying and the time of the day. For both drying systems it was observed that the temperature at 6.00 a.m. was about 29^{o} C and this increased for the Greenhouse type solar dryer to about 60^{o} C whilst the open sun drying increased marginally, the highest temperature recorded being 37^{o} C. Generally there were no significant differences between the days of drying suggesting that the effects expressed will be independent of the day of drying.

Table 1. Analysis of Variance of Temperature Changes and the Drying System

Source	Sum of Squares	D.F.	Mean Square	F	P value
Drying Days	204.12	13	15.703	0.36	0.9787
Drying method	2,783.04	1	2,783.04	64.26	0.0000
Time of day	4,373.45	4	1,093.36	25.25	0.0000
Residual	5,240.32	121	43.3084		
Total	12,600.90	139			

For both drying systems, the humidity changes with time followed the same trend (Figures 7, 8 and 9). It generally dropped with time but increased by end of the day. Comparatively, the relative humidity of OSD was higher than the GTSD throughout the day with 84 % recorded as the highest at 6:00 hours GMT and dropped by 12:00 hours GMT.

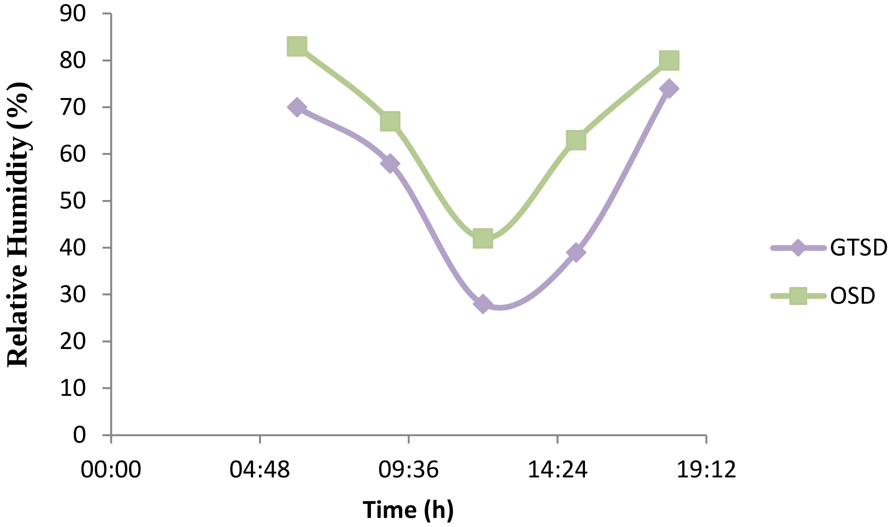


Figure 8. Day 1 Baseline Relative Humidity for GTSD and OSD

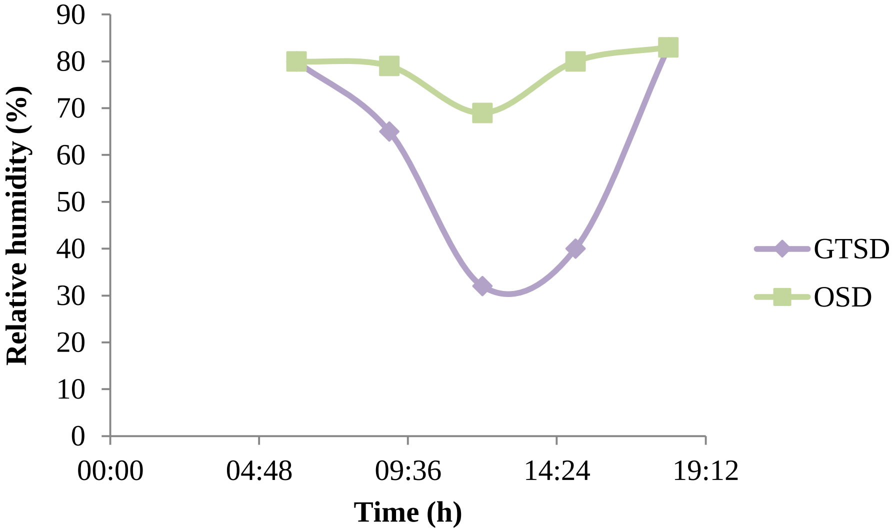


Figure 9. Day 7 Baseline Relative humidity for GTSD and OSD

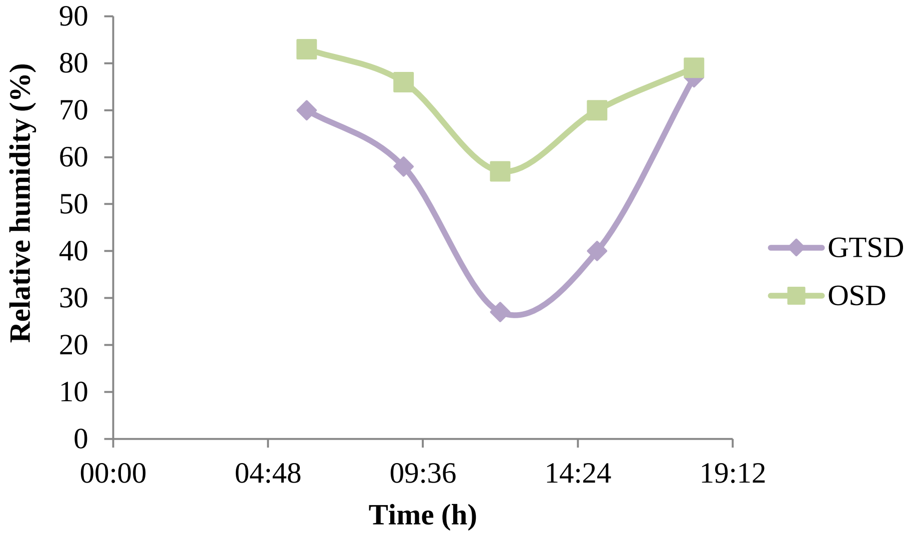


Figure 10. Day 14 Baseline Relative humidity for GTSD and OSD

Analysis of variance on the humidity data showed that the humidity was significantly influenced by the drying method and the time during the day (Table 2).

Table 2. Analysis of Variance on Humidity Changes and the Drying System

Source	Sum of Squares	D.F.	Mean Square	F	P value
Drying Days	1,020.34	13	78.4879	1.63	0.0849
Drying Method	8,896.11	1	8,896.11	185.17	0.0000
Time of day	25,066.80	4	6,266.71	130.44	0.0000
Residual	5,813.26	121	48.0434		
Total	40,796.50	139			

4.2 Drying of Cassava Chips in the Open sun (OSD) and Greenhouse Type Solar Dryer (GTSD)

4.2.1 Moisture Content of Dried Cassava Chips

Cassava is an important commodity in the Ghanaian food system and the drying of chips is very important in the cassava utilization. The cassava in the form of slices and chunks were dried in the two drying systems (OSD and GTSD) and each system showed moisture removal from the cassava chips (slices and chunks) as shown in Figures 10 and 11. The data for the cassava chips moisture are summarized in (Appendix 2). It was observed that there was moisture loss with drying time (Figures 10 and 11). Generally the GTSD observed a faster moisture removal for both the cassava slices and chunks than the OSD verifiably so because of higher temperature inside the GTSD.

However within both drying systems, the cassava slices demonstrated a faster moisture removal than the chunks after 24 hours and 36 hours of drying (Appendix 2). Because GTSD samples were left inside the dryer overnight, and OSD samples were covered with a polyethylene cover, it was observed that the moisture loss from the cassava slices and chunks under the two drying methods was not continuous. This is possibly because samples collected in the morning at 6:00 a.m. had picked up moisture from overnight temperature drop and increased humidity.

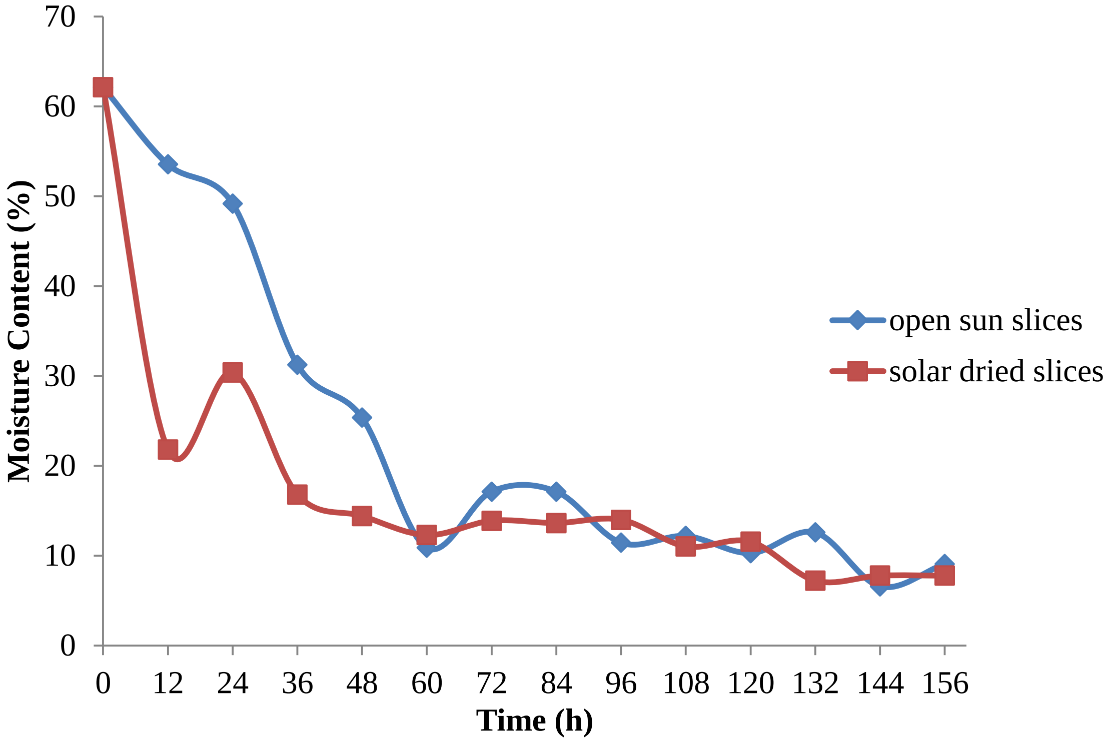


Figure 11. Moisture Variations between Open sun and solar dried cassava slices

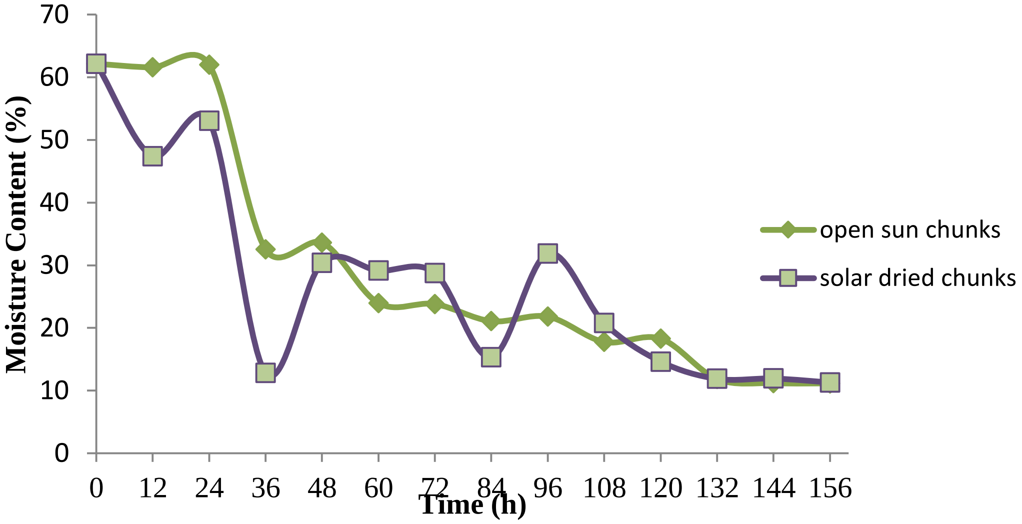


Figure 12. Moisture variation between Open sun and solar dried cassava chunks

Analysis of Variance on the moisture data delineating Sample Size, Drying Method, Time of Drying and Replication revealed that moisture removal was significantly influenced by sample size, time of drying and the drying method (Table 3). This clearly explains that the loss of moisture or moisture removal is dependent on the time of drying, the sample size and the drying method. It was observed that the highest temperatures for the two systems occurred during 12: 00 and 13:00 hours GMT as compared to 6:00 hours and 18: 00 hours GMT which recorded lower temperatures (Appendix 1). This explains that the time of day highly influenced the moisture removal. The two drying systems are different in terms of design considerations (material of construction, design concepts, temperature and humidity variations, etc.) and as such are expected to depict two different modes of moisture removal from the cassava samples. The two sample sizes (slices and chunks) though originating from the sample was observed to have significantly influenced the moisture removal. Firstly the two sizes have two different size dimensioning (slices with a thickness of 0.47 cm and chunks with a length of 4 cm, breadth of 2 cm and height of 1.5 cm) and will require different levels of heat penetration, moisture transfer within the sample to the surface and the final moisture removal from the surface. A thinner sample (e.g. slices) is easily penetrable by heat and can experience a rapid moisture loss than a thicker sample (e.g. chunks).

Table 3. Analysis of Variance of Moisture Content Changes and the Drying System

Source	Sum of Squares	D.F.	Mean Square	F	P value
Sample Size	2579.37	1	2579.37	73.34	0.0000
Replication	15.6287	2	7.81435	0.22	0.8010
Time of Drying	41038.6	13	3156.81	89.76	0.0000
Drying Method	711.547	1	711.547	20.23	0.0000
Residual	5275.24	150	35.1683		
Total	49620.4	167			

4.2.2. Drying Rates of Dried Cassava Chips

Drying of food commodities occur when there is a temperature gradient established between the drying system and the food commodity. Different types of products with different structural compositions may show different drying rates.

Drying rates of the cassava chips in the GTSD and OSD were monitored in a 12- hour interval. Data on drying rate is further summarized in Figures 12 and 13. From Appendix 3, generally GTSD recorded the highest drying rates of 3.361 g /g h and 1.232 g / g h for the cassava slices and chunks respectively after 12 hours of initiating the drying (Figures 12 and 13). This potential gives a good indication of the GTSD rendering a faster drying rate to food commodities with very high moisture contents. Generally in either of the drying systems (GTSD and OSD), drying rates reduced with time until it became gradual which suggests that drying of the samples is almost completed.

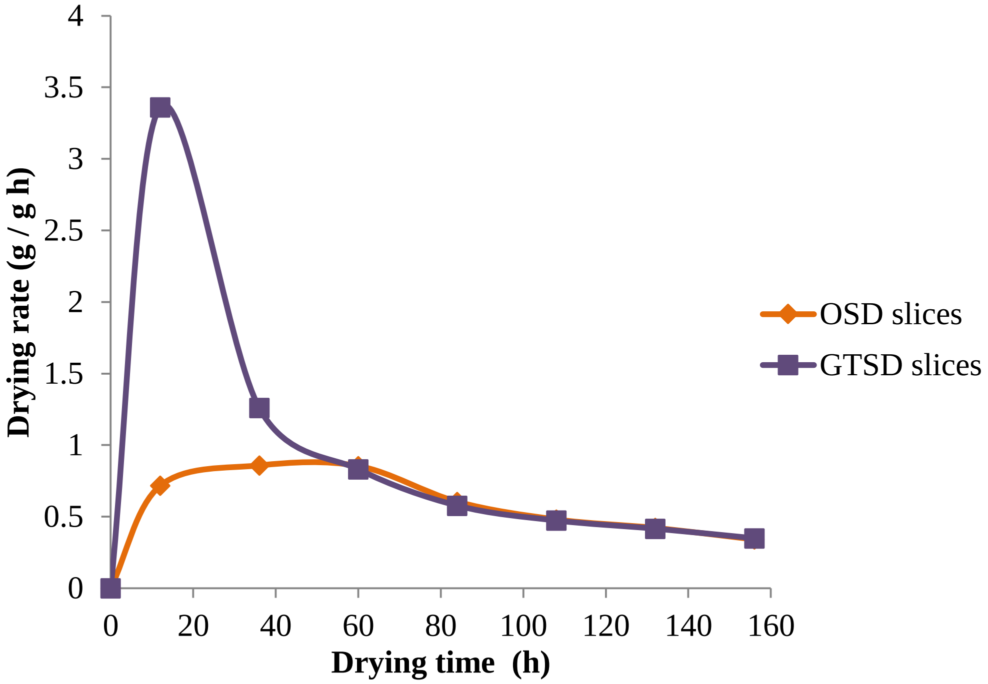


Figure 13. Drying rate curve for open sun dried and solar dried cassava slices

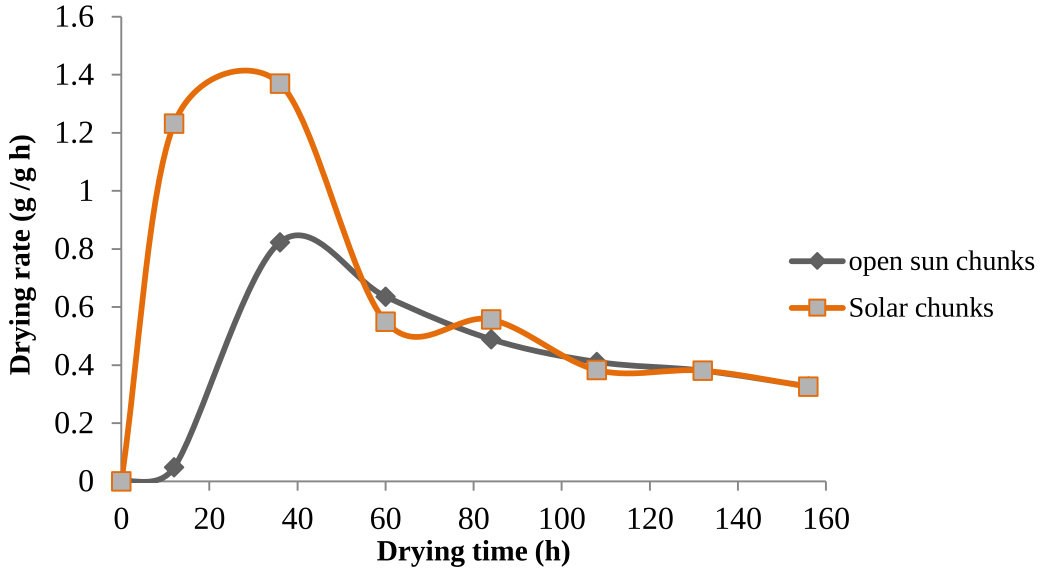


Figure 14. Drying rate curve of OSD and GTSD cassava chunks

4.3 Drying of Cocoa beans in the Open Sun Drying (OSD) and Greenhouse Type Solar Dryer (GTSD)

4.3.1 Moisture Content of Dried Cocoa beans

Cocoa is one of the cash crops in Ghana. Drying of cocoa beans remains one of the vital operations in the cocoa processing industry. The data obtained on moisture content of the cocoa beans with time is summarized in Appendix 4. Starting with an initial moisture content of 53.340 ± 0.678, the cocoa beans under the two drying systems demonstrated moisture loss with time. Cocoa beans after fermentation may still have some amount of a film of mucilaginous substance at its surface which serves as a barrier for moisture removal. Moisture removal from the cocoa beans can be observed as one occurring in different layers that is on its surface and from within the cocoa bean (nib) to its surface. After 12 h and 24 h of drying, the cocoa beans under both GTSD and OSD showed moisture absorption instead of moisture loss. Moisture removal from the cocoa beans was not continuous. Samples collected at 6 a.m. throughout the period of drying showed some amount of moisture absorption for both open sun drying and Greenhouse type solar drying systems. This may be due to the fact that when samples were left overnight, they absorbed moisture. This observation can be seen at Figure 14 where the sharp rise and fall of the curves depict the gain and loss of moisture.

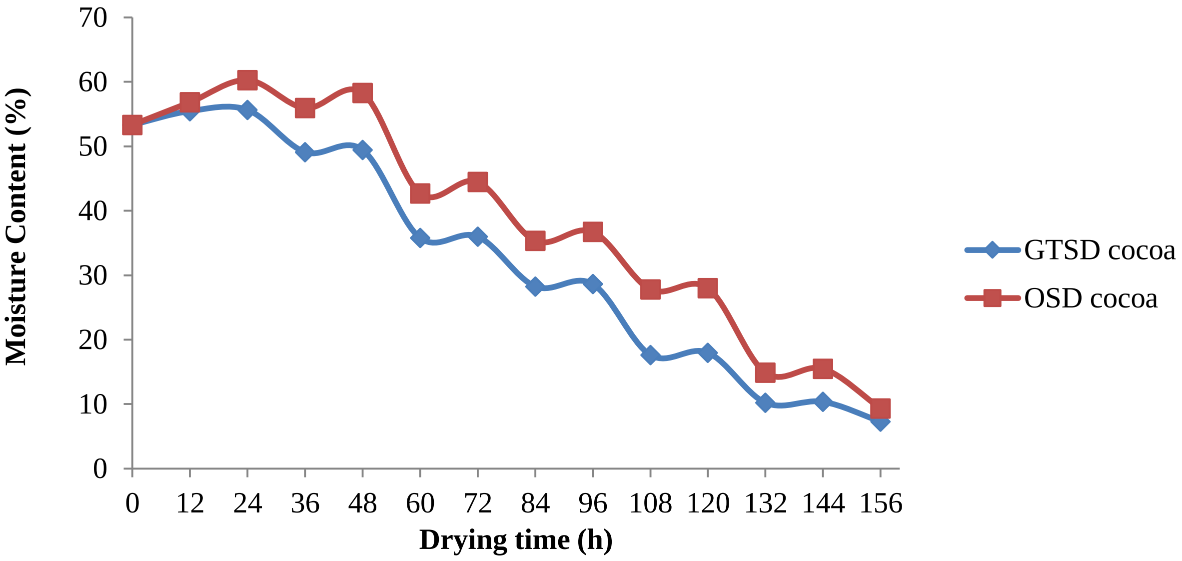


Figure 15. Moisture variation between OSD and GTSD Cocoa beans

Analysis of variance on the moisture data delineating Time of Drying, Drying Method and Replication revealed that indeed the moisture removal from the cocoa samples was significantly affected by drying method and drying time (Table 4). This means that for moisture removal to take place in the cocoa beans, the drying time and the drying method will highly influence it. Typically, temperature and humidity readings in each of the drying methods vary with time of the day and as such will exhibit different drying characteristics to the sample. Replication of the drying did not significantly affect the moisture removal from the samples (Table 4).

Table 4. Analysis of Variance of Cocoa beans and the Drying System

Source	Sum of Squares	D.F.	Mean Square	F	P value
Replication	38.0401	2	19.0201	2.80	0.0681
Time	24172.0	13	1859.39	273.46	0.0000
Drying Method	760.079	1	760.079	111.79	0.0000
Residual	455.563	67	6.79945		
Total	25425.7	83			

4.3.2 Drying Rate of Dried Cocoa beans

Drying rates of GTSD and OSD cocoa beans are summarized in (Appendix 5). Drying rates increased and decreased with time and this trend can be observed from the drying rates curves having multiple peak rises and falls (Figure 15). In this instance, the removal of moisture from the cocoa beans depended on three factors; conditions of the air, the properties of the cocoa beans and the drying method. A more humid surrounding offers the potential of moisture absorption into the cocoa beans. The drying rates generally can also be observed as being more gradual and slow which is a good sign (Figure 15). A drastic or faster drying rate can induce off flavors in the final dried cocoa beans. From Figure 15, between 0 h to 60 h, the two drying systems experienced the first initial thermal changes to reach the critical moisture contents after the drying period. The GTSD cocoa beans observed a rather shorter constant rate period (0.092 g / g h and 0.102 g / g h) than the OSD cocoa beans. This demonstrates that moisture loss occurred at the surface of the beans thus triggering a capillary suction of the moisture filled pores to replace the moisture loss at the surface of the cocoa beans. After the constant rate period, moisture contents of the beans tend to reduce and the capillary forces are no longer sufficient to transport moisture to the surface of the beans thereby rendering a dry layered bean surface. Both GTSD and OSD cocoa beans finally observe the falling rate period at 108 h to 156 h and 132 h to 156 h respectively.

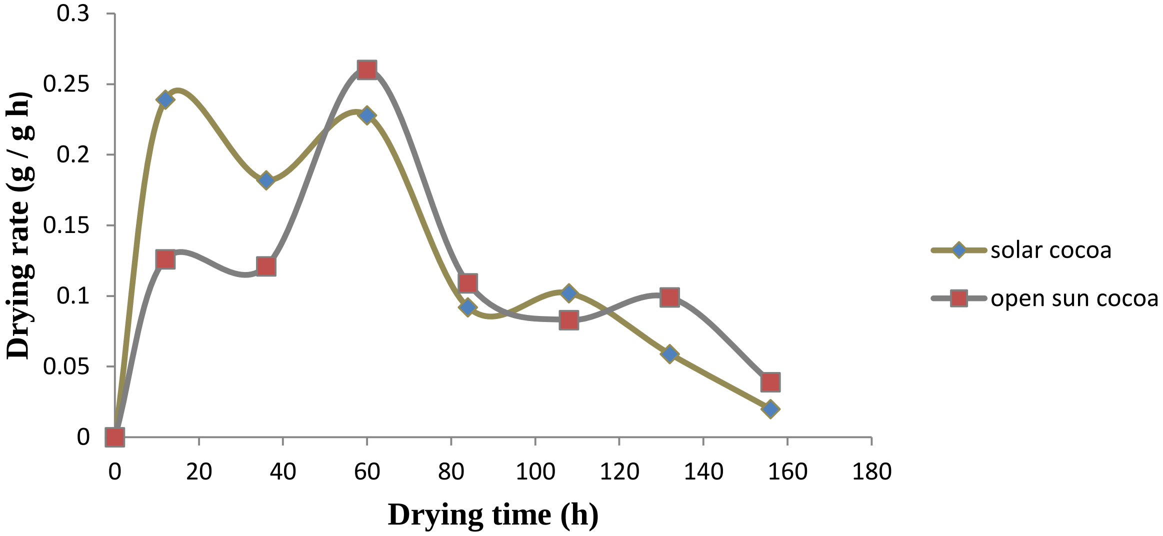


Figure 16. Drying rate of GTSD and OSD Cocoa beans

4.4 Develop a mathematical model for the Drying process using the Greenhouse type Solar dryer for the two food commodities

4.4.1 Mathematical modeling

To appreciate and understand the efficiency of the solar dryer and the effectiveness of the drying process, two existing mathematical models; the Henderson and Pabis and the Logarithmic models were selected for such purposes. According to Botelho *et al.* (2011), these models frequently present a good fit for the observed data and have been proposed by researches to simulate several processes in different engineering areas to obtain satisfactory results.

During the process of solar drying, it was quite complex to study the entire drying process. This complexity was due to several factors including heat transfer, mass transfer, vapour and liquid transfer which are highly dependent on the temperature gradients. The empirical approach to understanding the physical phenomena was mainly based on the study of the moisture content variation of the cassava and cocoa. This variation was basically between the drying of the product and the moisture content of the two food products with both as a function of time. The moisture contents of the product and the time gives way for the determination of the drying rates which will be used to draw experimental curves to analyze and highlight three distinct phases of drying as defined by (Koua *et al.,* 2009):

1. The introduction of temperature into the product
2. A constant drying rate phase
3. A falling rate phase

- **The introduction of temperature into the product inside the Greenhouse solar dryer**

This is basically the temperature rise of both the cassava and the cocoa when they were placed inside the greenhouse type solar dryer up to the point of attaining the wet bulb temperature which is the characteristic temperature of the greenhouse type solar dryer. This phase was mainly short relative to the total drying time of the food product and as such was considered negligible and not taken into account during the analysis of the drying rate curve.

- **A constant drying rate phase**

This phase is the first stage in the drying rate. It described the rapid movement of free water by capillary action (Henderson and Pabis., 1961) from inside of the cocoa and cassava samples to its surface. Drying rate at this phase was dependent on the drying conditions of the solar dryer and not the nature of the product. Once drying started moisture content, mc of the food samples changed to critical moisture content X_{cr} (i.e. the moisture content at which the constant rate drying period ends and the falling rate drying period starts). According to Henderson *and Pabis,* (1961), the constant drying phase rate phase is an adiabatic drying system equilibrium water removal from the surface of the product is equal to the rate of heat transfer to the surface.

Using the two samples: cocoa and cassava (slices and chunks), the rate of the water removal from the surface of the product was calculated separately and independently.

According to Henderson and Pabis (1961), the rate of water removal from the exposed surface of the food commodity is equal to the rate of heat transfer to its surface. This relationship is expressed by Equation 1.

$$\boldsymbol{L_v \frac{dm}{dt} = h_c S_p (T_a - T_p)}$$ **[Eqn. 1]**

$where\ h_c = surface\ heat\ transfer\ coefficient, S_p = surface\ area\ of\ the\ product,$

$T_a = Temperature\ of\ the\ drying\ air, T_p = Temperature\ of\ the\ food\ product,$

$L_v = Latent\ heat\ of\ water\ vaporization$

$\frac{dm}{dt}\ expresses\ the\ amount\ of\ water\ evaporated\ per\ unit\ time,$

$$but\ \boldsymbol{\frac{h_c}{L_v} = \frac{h_m}{R}}$$ **[Eqn. 2]**

Where $h_m = mass\ transfer\ coefficint\ , R = water\ vapor\ constant$

Substituting [Eqn. 2] into [Eqn. 1] gives;

$$\boldsymbol{\frac{dm}{dt} = \frac{h_m}{R} S_p \left(\frac{P_w}{T_p} - \frac{P_a}{T_a}\right)}$$ **[Eqn. 3]**

$$\boldsymbol{h_c = Nu \frac{\lambda}{D}}$$ **[Eqn. 4]**

$$Nusselt\ number, Nu = \left[\frac{0.825+0.387Ra^{\frac{1}{6}}}{\{1+(\frac{0.492}{Pr})^{\frac{9}{6}}\}^{\frac{8}{27}}}\right]$$

$$Rayleigh\ number, Ra = Gr \times Pr,$$

$$Grashof\ number, Gr = \frac{g\beta(T_S - T_\infty)L^3}{V^2}$$

The Water vapour partial pressure P_w of the product can be obtained using this relation below (Koua *et al*., 2009),

$$\boldsymbol{P_w = A_w P_{sat}\ \ and\ P_a = \frac{101325W_m}{W_m+0.622}} \qquad \textbf{[Eqn.5]}$$

Pure water saturated vapour pressure P_{sat} can be expressed as;

$$\boldsymbol{\log P_{sat} = 2.7877 + \frac{7.625T_p}{241.6+T_p}} \qquad \textbf{[Eqn.6]}$$

The equations above were used to determine the drying kinetics inside the greenhouse type solar using the Henderson and Pabis and Logarithmic models

- **Falling drying rate phase**

Falling drying rapid rate phase

During this phase, the capillary forces of the cassava and the cocoa samples were no longer sufficient to transport water to the surface of the product and as a result drying rate decreases rapidly. This was observed during the slow rate of loss of water towards the attainment of the final moisture contents of the two products. According to Koua *et al.* (2009), the slow drying rate is attributed to the evaporation of water by capillary action in midway of the internal transverse section of the food samples and somewhat diffusion phenomena occurring at the base of the food sample.

Falling drying slow rate phase

During this phase the samples were in the hygroscopic domain (water only exists only in a bound form) and as such the drying rate decreased slowly to reach the equilibrium moisture content, X_{eq} As temperature rose, the dried samples experienced some form of fissures which indicated that drying was finished. There was also a resistance to water vapour diffusion which is characterized by the equation below

$$\boldsymbol{X - X_f = C\, exp \frac{A_s}{R_{ds}} t} \qquad \textbf{[Eqn. 7]}$$

$where\ an\ intergral\ \ constant, C = X_o - X_{f,}$

$X_o = Initial\ moisture\ content,$

$X_f\ = final\ moisture\ content\ of\ food\ product, R_{ds}$= overall resistance to diffusion, t= time, $A_s = area\ of\ the\ product$

- **Mathematical modeling of solar drying curves**

Mathematical models are used to develop modeling curves of solar drying to elaborate a function verifying the following equation, $X_r = f(t)$

$$\boldsymbol{X_r\ is\ given\ by\ the\ equation, X_r = \frac{X - X_{eq}}{X_{cr} - X_{eq}}} \qquad \textbf{[Eqn. 8]}$$

The critical moisture content X_r is very complex to deduce and predict and as such models are used to decipher the critical moisture content. Knowledge of the critical moisture content enables one to stop the drying process so as to prevent the dehydration and shrinkage of the product.

4.4.2 Mathematical model constants

According to Botelho *et al.* (2011), the Henderson and Pabis and the Logarithmic model equations are [Xr= a exp (-kt)] and [Xr= a exp (-kt) +c] respectively. The model constants shown in Table 5 were obtained using Statistica data analysis, version 2003. Regression analysis was done by using the statistical routine to obtain the coefficient of correlation (r). The highest coefficient correlation was the criterion used to select the best equation to define the best model for the greenhouse type solar dryer.

Table 5: Mathematical models and respective constants and correlation coefficient (r)

Sample	**Henderson and Pabis** **X_r= a exp (-kt)**	**Logarithmic** **X_r= a exp (-kt) + c**
Solar dried slices	K=0.0327; a=0.5335; r= 0.9991	K=0.0229; a= 0.5937; c= -0.0770; r= 0.9985
Solar dried chunks	K=0.0231; a=0.5639; r= 0.9989	K=0.0165; a= 0.6176; c= -0.0746; r= 0.9978
Solar dried cocoa	K=0.0172; a=0.4646; r= 0.9990	K=0.00; a= 643.774; c= -643.352; r=0.9983

4.4.3 Variation of Moisture ratio and drying time between the two Mathematical Models

From the drying rate curves of the cassava chips and cocoa beans, it is apparent that drying rate decreases with drying time. There is a short constant drying rate drying period in these curves and a large falling rate. The two models clearly describe the drying sequence of both the cassava and cocoa samples. The curves are generated from the drying kinetics of cassava and cocoa using the greenhouse type solar dryer However, the Henderson and Pabis model best fits both the solar drying of cassava and cocoa beans because it has the highest coefficient correlations of 0.9991 for the cassava slices, 0.9989 for the cassava chunks and 0.9990 for the cocoa beans (Table 5).

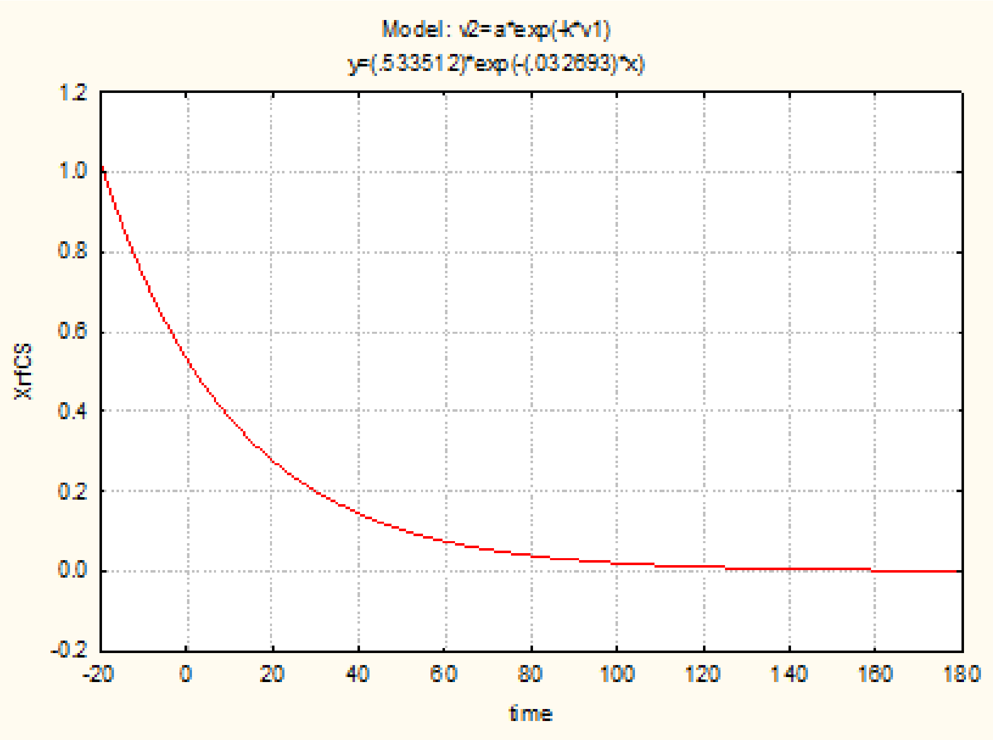


Figure 17: Henderson and Pabis model curve of moisture ratio curve for cassava slices

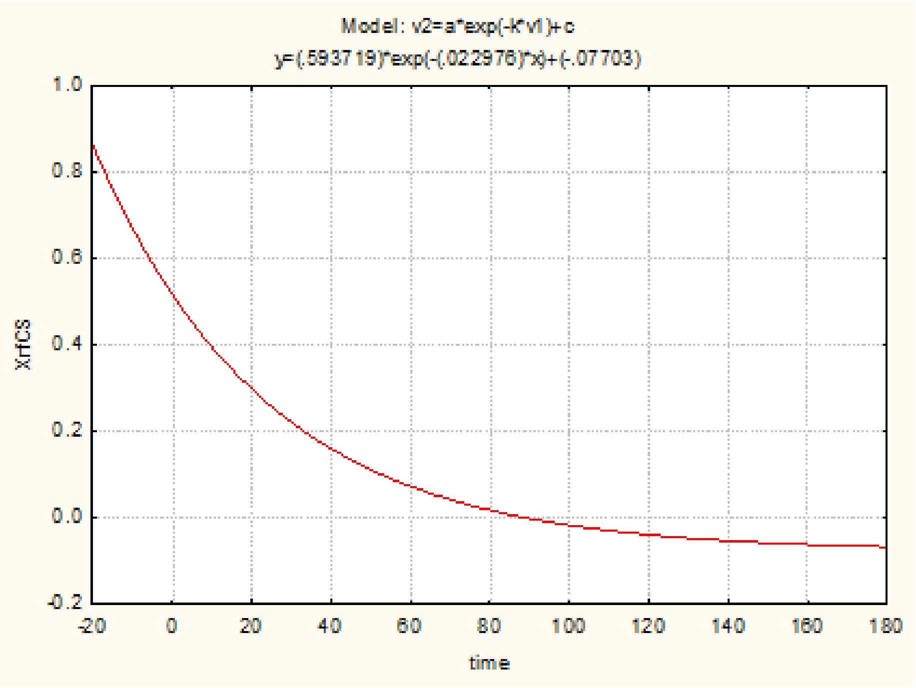


Figure 18: Logarithmic model curve of moisture ratio for GTSD cassava slices

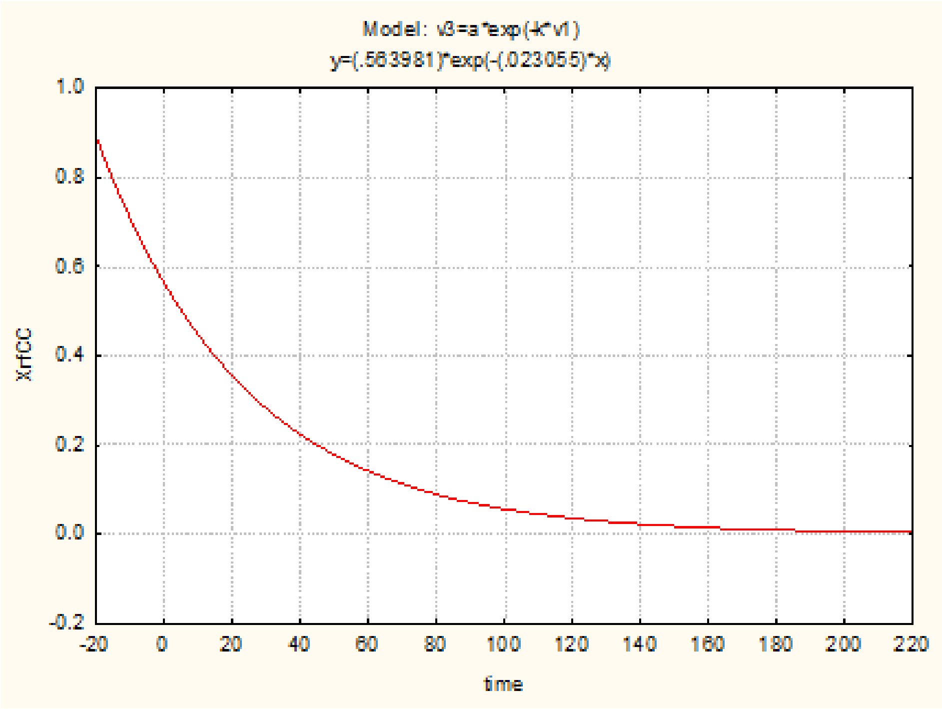


Figure 19: Henderson and Pabis model curve of moisture ratio curve for GTSD cassava chunks

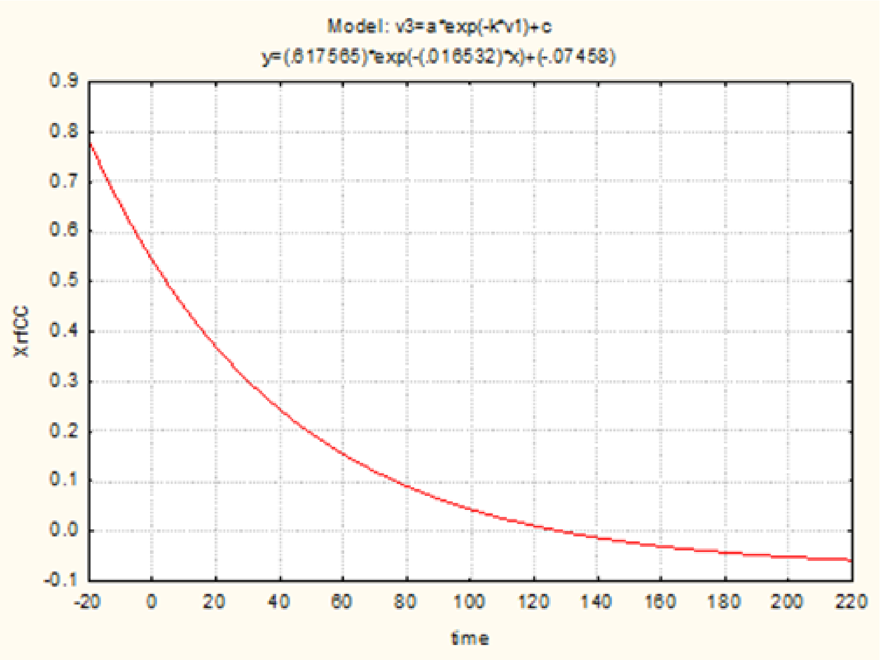


Figure 20: Logarithmic model curve of moisture ratio for GTSD cassava chunks

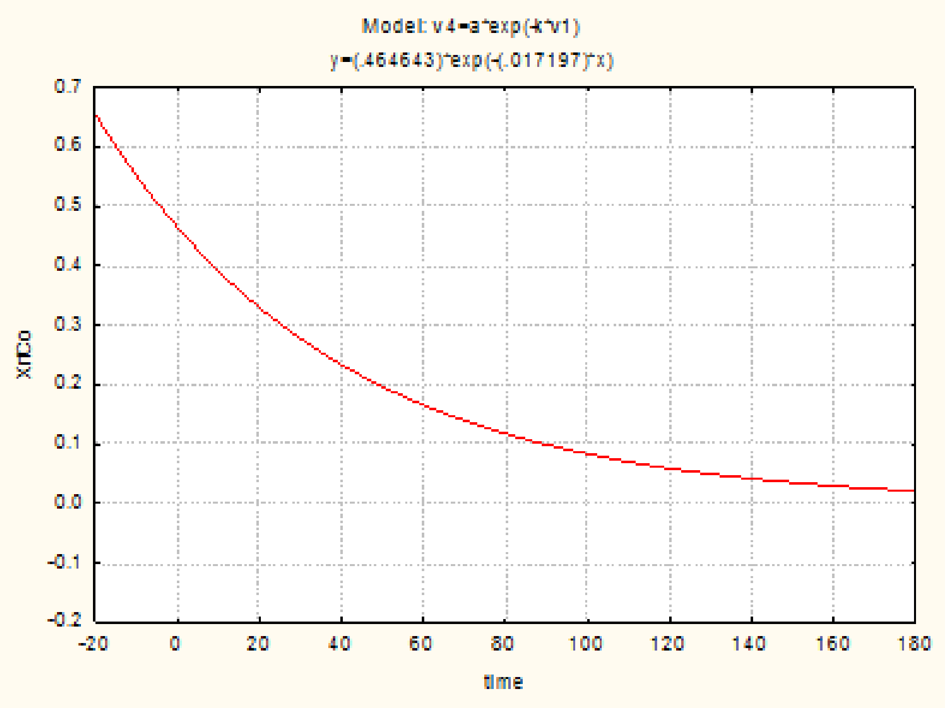


Figure 21: Henderson and Pabis model curve of moisture ratio curve for GTSD Cocoa beans

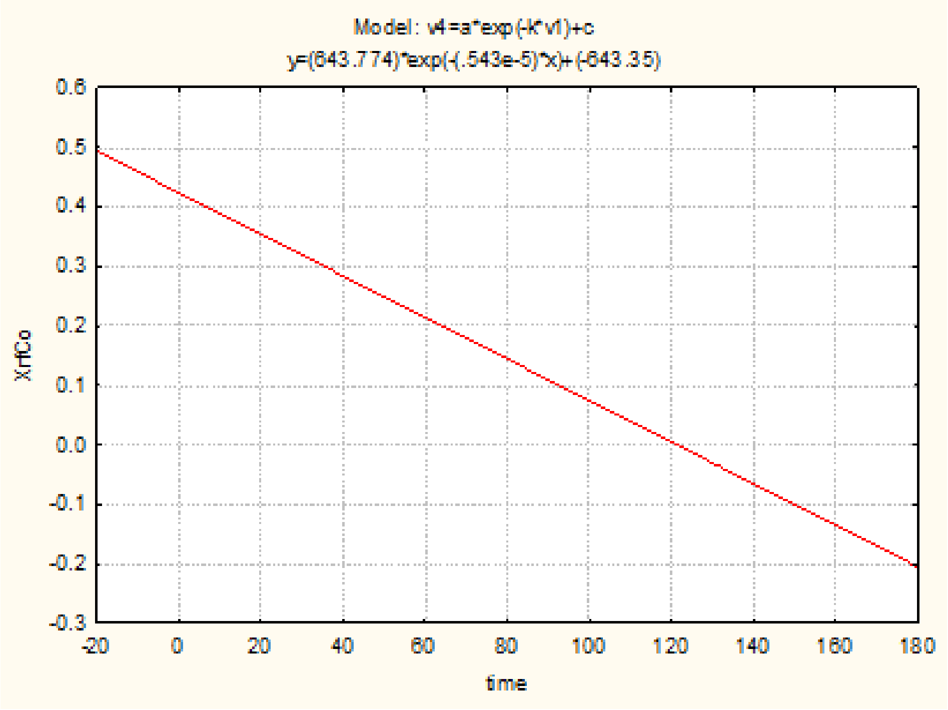


Figure 22: Logarithmic model curve of moisture ratio for GTSD Cocoa beans

Table 6: Model values of moisture contents at the different phases of drying

	Model moisture contents (g water / wet product)				
Sample	**X**	**X_f**	**X_{cr}**	**X_{eq}**	**X_r**
Cassava Slices	0.7268	0.0778	0.1403	0.018	5.9191
Cassava Chunks	0.7021	0.0968	0.1829	0.018	4.1484
Cocoa	3.1577	0.073	0.1762	0.022	20.335

4.5 Evaluate drying by comparing Quality indices of the dried samples

4.5.1 Water Activity

Water has been recognized as being very important to the stability of food products. Water activity of a food product can be used to predict the shelf stability of the product. This is because if a food product is kept below or above a shelf stable water activity then microbial growth may be inhibited or induced. The water activity for high quality cassava flour (HQCF) is 0.1 - 0.8 at 25°C (Dziedzoave *et al.*, 2003).

The water activity analysis performed on the cassava samples under the two different drying methods is summarized in Table 7. It can be observed that the resultant flours from the two sizes under the two different drying methods demonstrated water activity within the acceptable limits. This result signifies that the drying operation was efficient thus justifying that indeed solar energy plays a pivotal role during heat and mass transfer in a product undergoing drying. To further ascertain and commend the efficiency of the two drying methods, water activity analysis was performed on the dried cocoa beans (which possesses different structural composition than cassava). Summary of the water activity of the dried cocoa nibs can be found in Table 7. It clearly shows that if drying is performed on a food product to its acceptable final moisture content, its water activity will directly fall within the acceptable range. Hence the water activity of a dried sample is highly dependent on its moisture content. Aside the ensuring food safety, wholesomeness and consumer acceptability, an acceptable water activity ensures a good browning process which also enhances the final dried bean and chocolate colour during the roasting process in the Cocoa industry.

Table 7: Total average Water activity of samples

Sample	**Water activity / Temperature**
GTSD slices flour	0.398 / 28.61°C
GTSD chunks flour	0.413 / 28.72°C
OSD slices flour	0.417 / 28.93°C
OSD chunks flour	0.449 / 29.06°C
Solar dried Cocoa nibs	0.421 / 28.64°C
Open Sun dried Cocoa nibs	0.422 / 28.73°C

4.5.2 Colour Profile

A good food quality entails a lot; mainly the conformance to standards and consumer acceptability. Food colour is one of the obvious standards that consumers rely on during selection of a food commodity. From the consumers' perspective colour can only be perceived by the human eye. However, measuring the colour of foods goes beyond the human eyes perception. Using food quality standards, the colour profile helps to identify slight changes in overall presentation as well as alert potentially dangerous food contaminants or abnormalities. Colour of foods is perceived to alter slight or complete changes during food storage there determining the colour profile of foods helps to determine the shelf stability of the food. Appendix 6 summarizes the colour profile of the dried cassava samples under the two different drying methods.

According to the International Commission on Illumination (CIE) colour space which expresses L^*, a^*, b^*as the main colour components with respect to the human colour vision, L^* is for lightness, a^* is green to reddish region and b^* is blue to yellowish region. The lightness value, L^*, represents the darkest black at $L^* = 0$, and the brightest white at $L^* = 100$. The a^* axis represents the green–

red component, with green in the negative direction and red in the positive direction. The b* axis represents the blue–yellow component, with blue in the negative direction and yellow in the positive direction. Generally all two different sample sizes demonstrated some level of lightness with the GTSD slices (especially) obtaining the highest value of lightness (88.03 ± 0.03) signifying a potential of absolute whiteness of flour. Again, GTSD chunks also recorded the least grade of lightness among the samples. This informs that the final colour profile of the flour is dependent on the drying method and sample size. Another profound observation can also be made from Appendix 6 where the a^* value of the OSD chunks records in the negative range which tells us that there is a potential of a greenish tinge in its flour sample. This negative value confirms an observation made during the drying period where the surface of the chunks appeared greenish at the initial stages of drying.

Analysis of variance done on the colour profile delineating the Sample Size, Drying Method and Replication (Tables 8, 9 and 10) demonstrated that the Drying method and Sample size significantly influenced the final colour of the flour. It further explains that the drying method (either slow or fast drying rate, temperature and humidity levels, heat and mass transfers) and the sample size (slices, chunks) deeply contributes to Cassava flour. However the GTSD demonstrated the potential of retaining the ideal whiteness of cassava during drying thereby contributing to a good colour quality which will be acceptable to the consumer. It also provides the assurance of a longer lasting of colour components of cassava flour during storage for longer periods.

Table 8. Analysis of variance on the Colour Profile (L*) and the Drying System

Source	Sum of Squares	D.F.	Mean Square	F	P-Value
Sample	70.0833	1	70.0833	259.67	0.0000
Replication	0.0429167	2	0.0214583	0.08	0.9244
Drying method	27.4821	1	27.4821	101.82	0.0000
Residual	1.88928	7	0.269898		
Total	99.4977	11			

Table 9. Analysis of variance on the Colour Profile (a*) and the Drying System

Source	Sum of Squares	D.F.	Mean Square	F	P-Value
Sample	4.9152	1	4.9152	27.65	0.0012
Replication	0.262817	2	0.131408	0.74	0.5113
Drying method	2.5947	1	2.5947	14.60	0.0065
Residual	1.24415	7	0.177736		
Total	9.01687	11			

Table 10. Analysis of variance on the Colour Profile (b*) and the Drying System

Source	Sum of Squares	D.F.	Mean Square	F	P-Value
Sample	38.199	1	38.199	5508.53	0.0000
Replication	0.0202667	2	0.0101333	1.46	0.2949
Drying method	8.01968	1	8.01968	1156.49	0.0000
Residual	0.0485417	7	0.00693452		
Total	46.2875	11			

4.5.3 Particle Size Distribution (PSD)

The consumption of dried cassava chips in Ghana follows size reduction and the production of cassava flours. This flour is cooked into different dishes and provides a livelihood for many women Particle size distribution is a very important property in the flour industry. It depicts how structured the food commodity is. Flours are a heterogeneous mixture of particles of different densities and shapes (Dziedzoave *et al.*, 2003) and some textural properties can be deduced from the sample size distribution. Depending on the resultant product from the flour, particle size can be an impediment rather than a desirable trait during sensory tests and consumer surveys. Also there have been research on the use of cassava in composite wheat flours for the development of bakery, pastries and confectionery products (Nwabueze and Anoruoh, 2009). Cassava flours have equally been useful in the pharmaceutical industry.

According to Hatcher *et al.* (2009), the granulation characteristics of flours affect the rate of hydration and swelling capacity during processing, it was therefore of interest to establish the particle size distribution of the flours derived from the cassava chunks and slices of the drying method and sample size, particle size distribution of the resultant flour samples was performed (Appendix 7). A log-normal plot of the particle size distribution is shown in Figures 22 and 23.

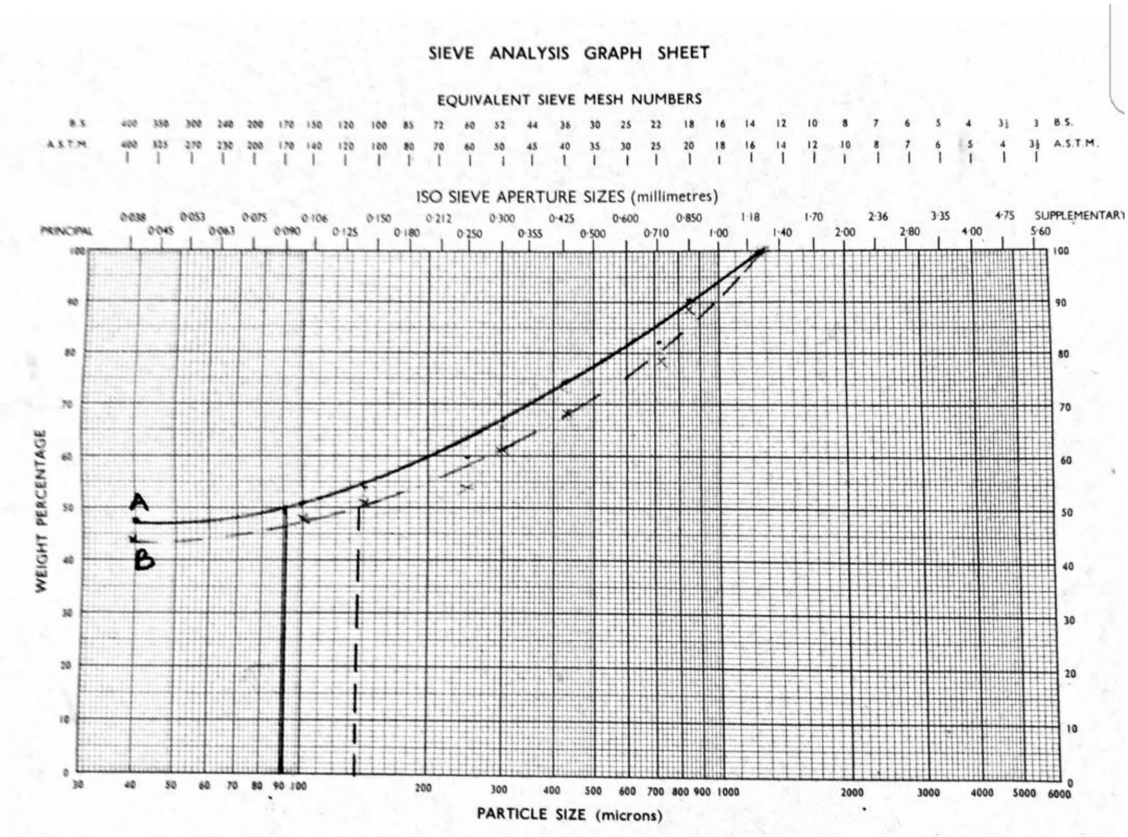


Figure 23. Cumulative frequency plot for PSD for GTSD slices and chunks

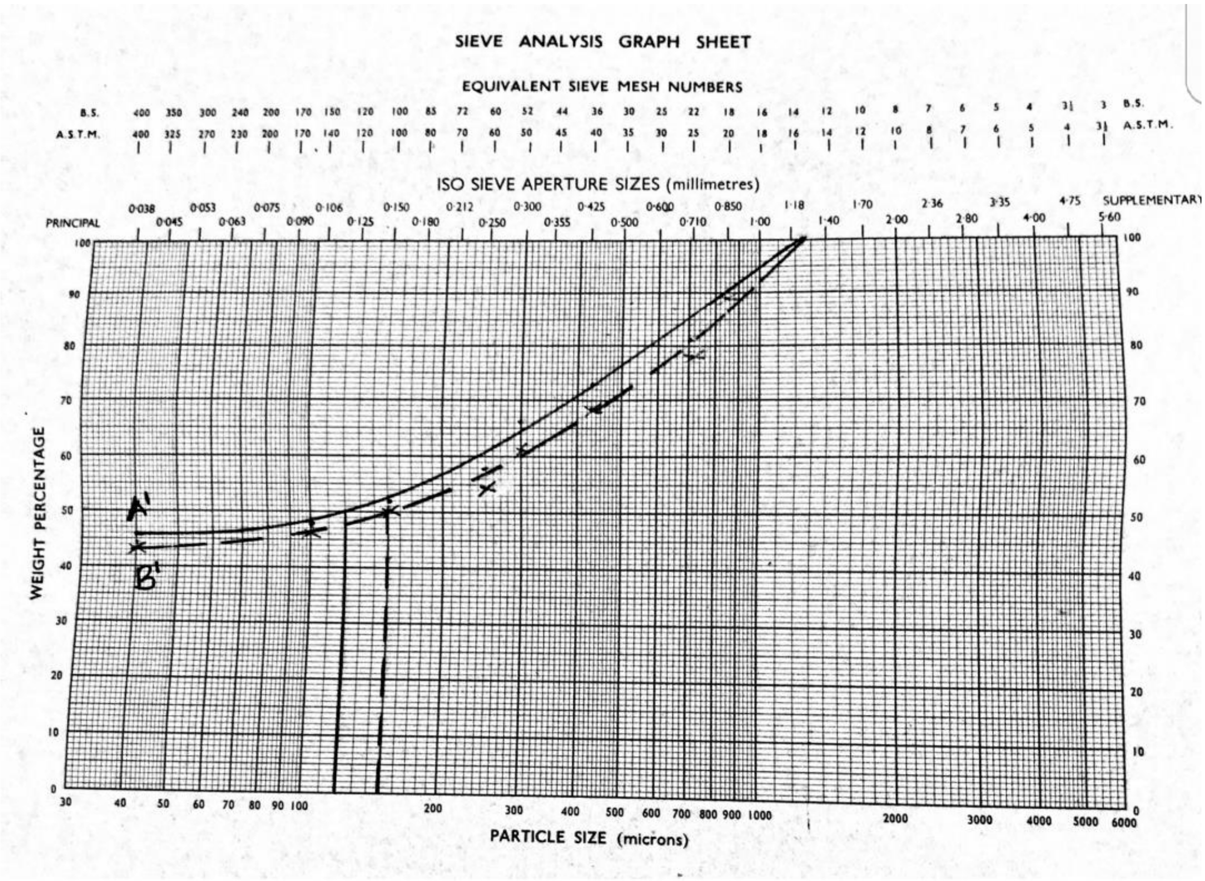


Figure 24. Cumulative frequency plot of PSD for OSD slices and chunks

From Figure 22, log normal plots of the particle size distribution for the GTSD slices and chunks can be seen. The SD_{50} for GTSD slices recorded at 92 µm (signifying the potential of sieving through 100 µm and <100 µm) which makes it a finer flour than the GTSD chunks with an SD_{50} recorded at 135 µm (Figure 22). The GTSD slices have a greater tendency of absorbing more water during hydration (Hatcher *et al.*, 2009) which has positive implication for flour functionality during processing. Larger particle flours require longer time for water to incorporate and tend to form larger dough lumps. The SD_{50} for the OSD cassava slices and chunks were recorded at 120 µm and 150 µm respectively depicting a better fineness for the cassava slices than the chunks (Figure 23).

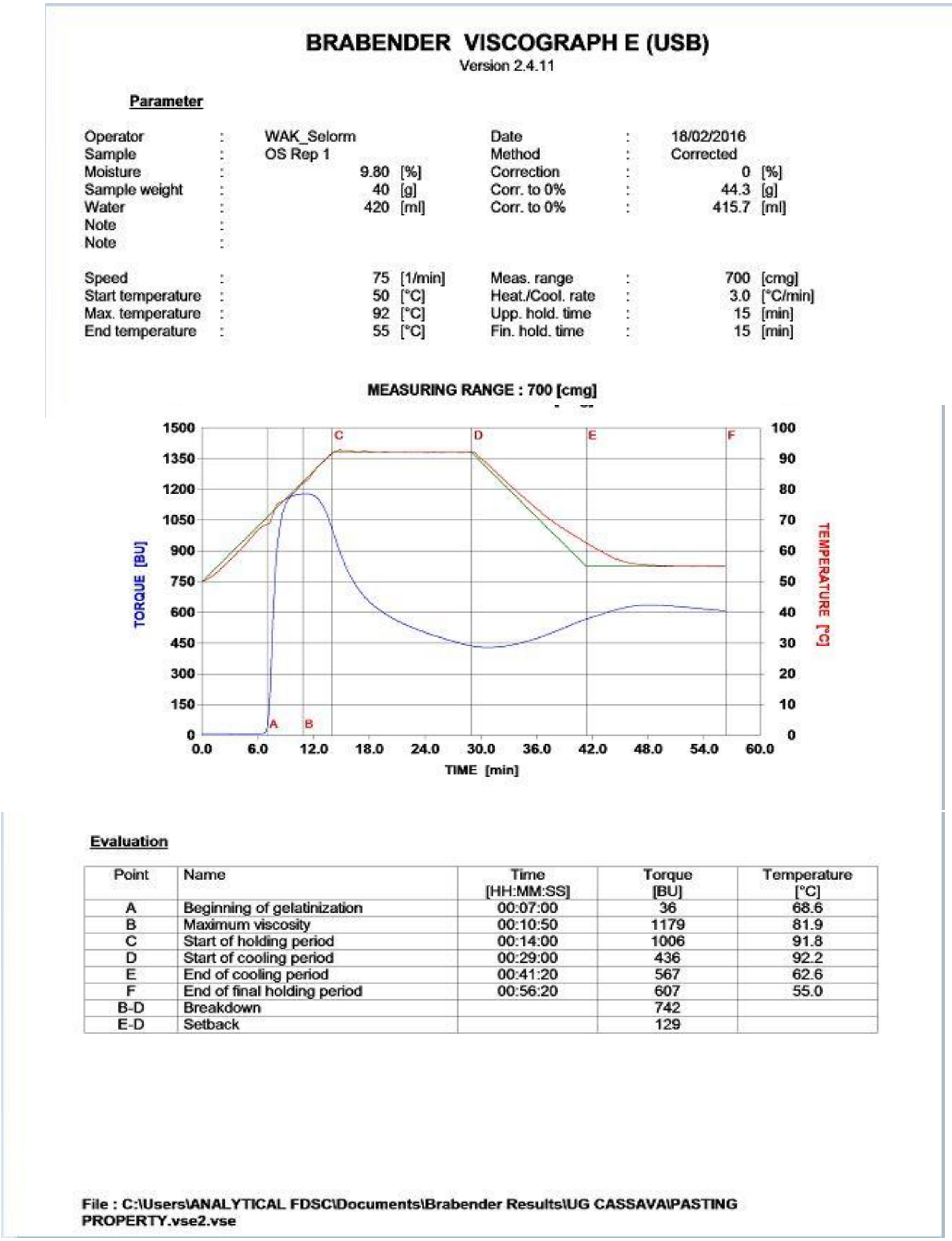
4.5.4 Pasting Property

One of the important properties of cassava flour is its cooked paste viscosity and how slurries emanating from flour derived from dried cassava behave. The consumption of cassava flour in Ghana may involve the cooking of slurries of flour into a stiff gelatinous food. It was therefore of interest to compare the outcome cooked paste characteristics of flours from of the drying of chunks and slices from cassava. A typical outcome of a run of the Amylograph is shown in Figure 24. Duplicate samples of the cassava flours showed the typical curves measured in the use of the amylograph delineating the pasting temperature (°C), the peak viscosity, viscosity at 92°C, viscosity at 92°C after holding for 15 mins, viscosity after cooling to 62°C , viscosity after holding at 62°C for 15 mins.

Average Critical parameters measured are summarized in Table 11. The pasting or gelatinization temperature is an index that denotes the initiation of gelling in the starch slurry. It can be seen in Table 11 that all the cassava flour samples irrespective of drying method and sample type showed gelatinization temperature of 69°C. This suggests that the starch in the resulting flours were not affected by the treatments given. Further analysis of the indices summarized in Table 11 show some variation in the viscosities notable among these is the viscosity after holding at 62°C for 15 minutes. This shows that all the flours showed stability of their cooked paste under the conditions used for the test. The data suggests that what is important is ensuring that the moisture in the cassava is removed to create a shelf-stable dried product. The resulting flour can be used for the different cassava products that require gelling when slurries are cooked.

Table 11. Amylograph Indices measured on cassava flours dried in the Open Sun and Greenhouse Solar Dryer.

INDEX	CASSAVA SLICES		CASSAVA CHUNKS	
	OSD	GTSD	OSD	GTSD
Gelatinization Temperature (°C)	68.6	68.6	69.3	69.0
Peak Viscosity (BU)	1185	1190	1148	1118
Viscosity at 92°C (BU)	1010	1121	1142	1116
Viscosity at 92°C-Hold	437	508	536	526
Viscosity at 62°C (BU)	568	670	624	658
Viscosity at 62°C-Hold	609	716	658	683
Breakdown (BU)	748	682	612	592
Set-Back Viscosity (BU)	131	162	88	132



BRABENDER VISCOGRAPH E (USB)
Version 2.4.11

Parameter

Operator	:	WAK_Selorm	Date	:	18/02/2016
Sample	:	OS Rep 1	Method	:	Corrected
Moisture	:	9.80 [%]	Correction	:	0 [%]
Sample weight	:	40 [g]	Corr. to 0%	:	44.3 [g]
Water	:	420 [ml]	Corr. to 0%	:	415.7 [ml]
Note	:				
Note	:				
Speed	:	75 [1/min]	Meas. range	:	700 [cmg]
Start temperature	:	50 [°C]	Heat./Cool. rate	:	3.0 [°C/min]
Max. temperature	:	92 [°C]	Upp. hold. time	:	15 [min]
End temperature	:	55 [°C]	Fin. hold. time	:	15 [min]

MEASURING RANGE : 700 [cmg]

Evaluation

Point	Name	Time [HH:MM:SS]	Torque [BU]	Temperature [°C]
A	Beginning of gelatinization	00:07:00	36	68.6
B	Maximum viscosity	00:10:50	1179	81.9
C	Start of holding period	00:14:00	1006	91.8
D	Start of cooling period	00:29:00	436	92.2
E	End of cooling period	00:41:20	567	62.6
F	End of final holding period	00:56:20	607	55.0
B-D	Breakdown		742	
E-D	Setback		129	

File : C:\Users\ANALYTICAL FDSC\Documents\Brabender Results\UG CASSAVA\PASTING PROPERTY.vse2.vse

Figure 25. Typical Brabender Visco-Amylograph of Cassava Flour Samples

An analysis of variance was performed on the data obtained from the pasting property analysis delineating Sample size and drying method (Tables 12, 13, 14, 15, 16, 17 and 18). From Table 12, it can be observed that the peak viscosity was significantly influenced by the sample type (slices or chunks). Generally the slices tended to show a higher peak viscosity (1,185-1,190 B.U.) against the slices (1,118-1,148 B.U.) (See Table 12)

Table 12: Analysis of Variance for Peak Viscosity for the dried Cassava chips and the Drying System

Source	Sum of Squares	D.F.	Mean Square	F	P-Value
Sample type	4005.13	1	4005.13	10.10	0.0246
Drying method	21.125	1	21.125	0.05	0.8266
Residual	1982.63	5	396.525		
Total	6008.88	7			

The viscosity at 92°C reflects the ease of cooking of the starch in the flour. Analysis of variance on the data suggests that neither the sample type nor the drying method had significant effect of this index (Table 13). This further supports the assertion that the products arising from the drying have similar functional cook paste characteristics. Similarly the viscosity at 92°C-Hold (Table 14), did not show any significant effect of either the sample type or drying method on this index.

Table 13: Analysis of Variance for Viscosity at 92C for the dried Cassava chips and the Drying System

Source	Sum of Squares	D.F.	Mean Square	F	P-Value
Sample type	1682.0	1	1682.0	0.65	0.4572
Drying method	162.0	1	162.0	0.06	0.8126
Residual	12965.5	5	2593.1		
Total	14809.5	7			

Table 14: Analysis of Variance for Viscosity at 92H for the dried Cassava chips and the Drying System

Source	Sum of Squares	D.F.	Mean Square	F	P-Value
Sample type	2211.13	1	2211.13	1.89	0.2277
Drying method	55.125	1	55.125	0.05	0.8368
Residual	5851.63	5	1170.33		
Total	8117.88	7			

The viscosity at 62^{o} C measures the setback that occurs when the hot paste is cooled. Analysis of variance showed that this index is significantly influenced by the drying method (Table 15). From the data the GTSD tended to have a higher viscosity at 62°C (Table 15).

Table 15: Analysis of Variance for Viscosity at 62C for the dried Cassava chips and the Drying System

Source	Sum of Squares	D.F.	Mean Square	F	P-Value
Sample type	105.125	1	105.125	0.18	0.6905
Drying method	5778.13	1	5778.13	9.79	0.0260
Residual	2949.63	5	589.925		
Total	8832.88	7			

A similar trend was observed with the data for the samples held for 15 minutes at 62°C. Analysis of variance on the data (Table 16) showed a significant effect of drying method.

Table 16: Analysis of Variance for Viscosity at 62H for the dried Cassava chips and the Drying System

Source	Sum of Squares	D.F.	Mean Square	F	P-Value
Sample type	40.5	1	40.5	0.07	0.8087
Drying method	5724.5	1	5724.5	9.21	0.0289
Residual	3109.0	5	621.8		
Total	8874.0	7			

The breakdown viscosity is linked to the paste stability or lack thereof during the cooking of starch slurries. The breakdown viscosity measures the ability of the flour to withstand heating and shear stress during cooking. This index is significantly affected by the sample type (Table 17).

The setback viscosity gives an indication about retro gradation tendency of starch in the cassava slices and chunks flour. The Setback viscosity of the flour was observed to be dependent on the drying method. According to Adebowale *et al.*, (2005), Setback viscosity has been correlated with textural structure influenced by the type of drying method and this justifies that observation (Table 18).

Table 17: Analysis of Variance for Breakdown for the dried Cassava chips and the Drying System

Source	Sum of Squares	D.F.	Mean Square	F	P-Value
Sample type	12246.1	1	12246.1	6.91	0.0466
Drying method	120.125	1	120.125	0.07	0.8050
Residual	8859.63	5	1771.93		
Total	21225.9	7			

Table 18: Analysis of Variance for Setback for the dried Cassava chips and the Drying System

Source	Sum of Squares	D.F.	Mean Square	F	P-Value
Sample type	1378.13	1	1378.13	5.55	0.0650
Drying method	4656.13	1	4656.13	18.77	0.0075
Residual	1240.63	5	248.125		
Total	7274.88	7			

4.5.5 Bean cut test of GTSD and OSD Cocoa beans

Drying of cocoa beans does not only remove moisture but enhances the final bean quality. The preferred designation is fully brown beans as compared to slaty, purple and fully brown and overly brown. Cocoa beans have been observed to undergo fermentation during its initial stages of drying for which temperature plays a vital role. Extreme temperatures therefore can inhibit, halt and also trigger an overly fermentation of cocoa beans.

To check on the quality of the preliminary work on drying of cocoa beans the standard method of evaluation of the cut test was applied on the 300 beans from the open sun and solar drying method (Table 19). It was observed that both drying systems lead to the production of predominantly fully brown beans, i.e. 83.7 % and 97 % for the OSD and the GTSD dried samples respectively. This suggests that both drying systems provided the environment for producing acceptable beans. It was further observed that 3.0 % of cocoa samples dried in the GTSD were overly brown in colour which is associated with over fermentation partly linked with extreme drying temperature. This suggests that the higher temperatures of 55°C recorded between 12:00 and 13:00 hours GMT inside the GTSD may be the cause of the overly fermentation of the cocoa beans.

Table 19 further showed the presence of slaty beans from the open sun drying depicting under-fermentation. Slaty cocoa beans cause bitterness and contribute an astringent taste in chocolate production. Under fermentation of cocoa beans is one of the major setbacks in the cocoa industry. While the drying of cocoa beans is underway, the beans are expected to continue fermentation.

Table 19. Number of beans and their bean test scores

Mode of Drying	Score			
	1	2	3	4
OSD	38 (12.7%)	0	262 (87.3%)	0
GTSD	0	0	291 (97%)	9 (3%)

Bean Cut Scores

1 – Slaty beans 2- Purple beans 3- Fully brown beans 4- Overly brown beans

4.5.6 Free fatty acids (FFA) of Dried Cocoa beans

The quality of raw cocoa beans depends widely on their free fatty acid. The free fatty acid content of cocoa beans is influenced by duration of fermentation and the final moisture content of the beans. Table 20 summarizes the observed results on the FFA. Drying the cocoa beans in either of the drying method resulted in final moisture content within the acceptable range (Appendix 4). FFA of cocoa beans is directly dependent on the profile of the bean fermentation and indirectly on drying. Cocoa beans have been identified with continuous fermentation during drying. This means that a conducive drying temperature affects the fermentation profile which in turn affects the free fatty acids of the cocoa beans. FFA are carboxylic acids released from triglycerides through the effect of oxidation. However extremely high FFA content remains a threat to the value of cocoa in the food industry and the global market thus drying plays an important role. The higher amount of free fatty acids is an indication of low cocoa bean quality and can cause chocolate bar or cocoa paste from hardening efficiently to enable the ‘popping’ in chocolate bars (Choudhary and Graver, 2013). The European parliament and European council directive limits the maximum FFAs content to 1.75% oleic acid equivalent in cocoa butter (EEC, 1973). This shows that the OSD and the GTSD provided cocoa bean with acceptable FFA values.

Table 20: Free fatty acid (% Oleic acid) of Cocoa beans

Sample	**Free Fatty Acids (% Oleic acid)**
GTSD cocoa beans	0.47
OSD cocoa beans	0.51
Maximum allowable FFA level	1.75

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATION

5.1 Conclusions

The rationale behind the design and construction of the Greenhouse-type solar dryer (GTSD) was to help combat the challenges associated with open sun drying (OSD). The study showed that it is possible to construct a greenhouse-type dryer using local materials. The GTSD when operated without food commodity showed that the highest temperature attained was of 60^{o}C which mostly occurred between 12:00 and 13:00 hours GMT. Relative humidity generally observed a trend where it gradually dropped from 6:00 hours till 12:00 midday for the GTSD (83-42) % and OSD (70-28) % systems. The open sun drying observed higher humidity levels of 84 % at 18:00 hours GMT. The drying patterns for both the cassava and cocoa suggested that the fastest moisture removal occurred during 12:00 and 13:00 hours GMT due to high temperatures of 60^{o}C recorded inside the GTSD.

It is further concluded that the time of the day, drying method and sample type influenced the drying of the cassava slices and chunks. Overall, the cassava slices demonstrated faster drying rate than the cassava chunks under the GTSD which clearly depicts that the rate of moisture removal is dependent on the sample size. The cassava slices and chunks exhibited a different moisture transfer from within the internal structure and their surfaces which affected the rate of moisture removal.

The characteristics of the flours produced from the dried cassava samples showed that both the Greenhouse-type dryer and the open sun yielded products with similar functional properties. This suggests that the efficiency for the drying system will be more of a determining factor in the selection of the method for moisture removal.

Based on the data obtained on the mathematical modelling, the Henderson and Pabis and the Logarithmic models were adequate in describing the drying phenomena of both the cassava and cocoa beans samples. The Henderson and Pabis models can better express the drying profile of the cassava and cocoa samples than the Logarithmic model.

The Greenhouse type solar dryer (GTSD) produces cocoa beans with higher bean quality compared to the Open sun drying (OSD) since the cocoa bean cut test showed a higher percentage cocoa bean quality for the GTSD as compared to OSD.

5.2 Recommendation

Based on the research work done and the results and observations made, it is recommended that the design of the GTSD be improved with regards to:

i. The number of the polyethylene cover be increased to ensure a stronger resistance to wears and tears during extreme temperatures or instantaneous cooling effect, strong winds and a firmer stability

ii. The introduction of shelves to maximize the usage of space and also provide a versatility on the usage of the GTSD for other food commodities

iii. Temperature regulation to prevent under drying, overly drying and dehydration of food commodities.

iv. An additional heating component and extractors to provide continuous drying during nightfall, efficient heat removal and as an alternative source of heat in the event of rainfall and unfavorable weather conditions

REFERENCES

Adebowale, A.A., Sanni, L.O., and Awonorin, S.O. (2005). Effect of Texture modifiers on the physicochemical and sensory properties of dried Fufu. J. of Food Sc. and Technol. Int. 11(5): 273-282

Afoakwa, E.O. (2014). Cocoa Production and Processing Technology. 1st Edition. CRC Press. pp 312-368

Afoakwa, E.O., Quao, J., Budu, A.S., Takrama, J. and Saalia, F.K. (2010). Chemical and Physical Quality characteristics of Ghanaian cocoa beans as affected by pulp pre conditioning and fermentation. Chemical composition and Cyanogenic potential of Traditional and high yielding CMD resistant Cassava (*Manihot esculenta Crantz*) varieties. Int. Food Res. J. 19 (1):175-181

Akpinar, E.K., Y. Bicer, and C. Yildiz. (2003). Thin layer drying of red pepper. J. of Food Eng. 59:99-104.

Amer, B.M.A., Hossain, M.A., Gottschalk, K. (2009). Design and Performance Evaluation of a new hybrid solar dryer for banana. Energy Conversion and Management. 51(4): 813-820

AOAC. Official Methods of analysis. 18th edition. Association of Official Analytical chemists; Arlington, VA, USA: 2005; method 930.15.

Ayyappan, S., Mayilsamy, K., Sreenarayanan, V.V. (2016). Performance improvement studies in a solar greenhouse dryer using sensible heat storage materials. J. of Heat and Mass Transfer. 52(3):459–67.

Bevill, V.D. and Brandt, H. (1968). A Solar Energy Collector for heating air. Solar Energy. 12(1):19-20

Botelho, F.M., Corrêa, P.C. C., Oliveira, G.H.H., Goneli, A.L.D., Resende, O., Campos S. C. (2011). Mathematical modeling of the drying process of corn ears. J. of Scientific Agronomy. 33(4):575-581

Cocoa and chocolate manual (2009). A Source Book for Sustainable Cocoa Production. Cocoa Research Institute of Ghana

Chauhan, P. S., Kumar, A., Gupta, B. (2016). A review on thermal models for Greenhouse dryers. Renewable Sustainable Energy Review. 75: 548- 558

Chavez, A.L., Sanchez, T., Jaramillo, G., Bedoya, J.M., Echeverry, J., Bolanos, E.A., Ceballos, H. and Iglesia, C.A. (2010). Variations of quality traits in cassava roots evaluated in landraces and improved clones. *Euphytica* 143: 125-133.

Doymaz, I. (2007). The Kinetics of forced convective air drying of pumpkin slices. J. of Food Engineering 79(1):243-248

Dziedzoave, N.T., Graffham, A.J., Boateng, E.O. (2003). Training manual for the production of high quality Cassava Flour. Food Research Institute, Accra- Ghana. pp 1-36

Ekechukwu, O.V. and Norton, B. (1999). Review of Solar-Energy Drying Systems 1: An Overview of Solar drying technology. Energy Conversion & Management Journal. 40(6):615-655.

Erbay, Z. and Icier, F. (2009). A review of thin layer drying of foods. Theory, modelling and experimental results. Critical Reviews in Food Science and Nutrition. 50(5):441-464

Fudholi, A., Sopian, K., Ruslan, M.H., Alghoul, M.A. and Sulaiman, M.Y. (2010). "Review of Solar Dryers for Agricultural and marine products". Renewable and Sustainable Energy Reviews. 14:1-30.

Gatea, A. (2010). Design, Construction and Performance evaluation of solar maize dryer. J. of Agric. Biotechnol. and Sust. Dev. 2(3):39-46

Ganguly, A., Misra, D., Ghosh, S. (2010). Modeling and analysis of solar photovoltaic-electrolyzer-fuel cell hybrid power system integrated with a floriculture greenhouse. J. of Energy and Buildings. 42(11): 2036-2043

Guehi, T.S., Zahouli, I.B., Ban-Koffi, L., Fae, M.A. and Nemlin, J.G. (2010). Performance of different drying methods and their Effects on the Chemical Quality attributes of raw Cocoa material. Int. J. of Food Sci. and Technol. 45(8):1564–1571.

Hadnađev, T.D., Pojić, M., Hadnađev, M. and Torbica, A.(2011). The Role of Empirical Rheology in Flour Quality Control. Wide Spectra of Quality Control

Hatcher, D.W., Bello, G.G., Anderson, M.J. (2009). Flour particle size, starch damage, and alkali reagent: impact on uniaxial stress relaxation parameters of yellow alkaline noodles. Cereal Chem. J. 86:361–368

Henderson, S.M. and Pabis, S. (1961). Grain drying theory: Temperature effect on drying coefficient. J. of Agric. Eng. Res. 6(3):169-174

Hii, C.L. and Ong, S.P. (2012). Quality characteristics of solar dried products in solar drying. Fundamentals, Applications and Innovations, Singapore. Drying of foods, vegetables and fruits. 3:111-121

Horwitz, W. and Latimer, G. W. (2005). Official Methods of analysis of Association of Official Analytical Chemists International. AOAC International, USA.

International Cocoa Organization (ICCO), (2009). The Chocolate Industry http://www.icco.org/about/chocolate.aspx

IOCCC. International Office of Cocoa, Chocolate and Sugar Confection. (1996). Determination of free fatty acids (FFA) content of Cocoa fat as a measure of cocoa nib acidity. Analytical Method No. 42-1993.

Jain, D. and Tiwari, G.N. (2003). Thermal aspect of open sun drying of various crops. Energy, 28, 37-54

Janjai S., Khamvongsa, V., Bala, B. K. (2007). Development, design, and performance of a PV ventilated greenhouse dryer. Int. Energy J. 8(4):249–258

Janjai, S. and Bala, B.K. (2012). “Solar Technology”, Food Engineering Reviews. 4:16-54

Jinap, S., Thien, J. and Yap, T.N. (1994). Effect of drying on acidity and volatile fatty acids content of Cocoa beans. J. Sci. Food Agric. 65(1):67-75

Kashaninejad, M., Mortazavi, A., Safekordi, A., Tabil, L.G. (2007). Thin layer drying characteristics and modelling of Pistachio nuts. J. of Food Eng.78(1): 98-108

Kumar, M., Sunil, K.S., Pankaj, K. (2016). Progress in solar dryers for drying various commodities. J. of Renewable and Sustainable Energy Reviews 55: 346-360.

Lasisi D. (2014). A Comparative Study of effects of Drying Methods on Quality of Cocoa Beans. Int. J. of Eng. Res. and Technol. 3(1):991-996

Marion, G. & Lawson, D. (2008). An introduction to mathematical modelling. Bioinformatics and statistics, Scotland. pp 1-25

Mortezapour, H., Ghobadian, B., Khoshtaghaza, M., Minaei, S. (2012). Performance analysis of a two way hybrid photovoltaic thermal solar collector. J. of Agric. Sci. Technol. 14(4):767-780

Mujumdar, A.S., Huang, L. X. and Xiao D. C. (2010). An overview of the recent advances in Spray-drying. Dairy Science and Technology Journal. 90(2-3):211-224

Mulato, S. and Mühlbauer, W. (2016). Solar Assisted Cocoa Processing Center for Smallholders Use. Innovative Technologies for Agricultural and Marine Products. Publications of the Islamic Educational, Scientific and Cultural Organization -ISESCO- 1427H

Musa, A.N. (2012). Drying characteristics of cocoa beans using an artificial dryer. J. of Eng. and applied Sci. 7(2):194-197

Nayak, S., Tiwari, G.N. (2008). Energy and exergy analysis of photovoltaic thermal integrated with a solar greenhouse. Energy and Buildings. 40(11):2015-2021

Neumaier, A. (2004). Mathematical modelling; modelling languages in mathematical optimization. Springer. pp 45-62

Nielson, D.S. Teniola, O.D., Ban-Koffi, L., Owusu, M., Anderson, T. and Holzapfel, W. (2007). The Microbiology of Ghanaian cocoa fermentation analyzed using culture dependent and culture independent methods. Int. J. of Food Microbiology 114 (2):168-186.

Nwabueze, U. T. and Anoruoh, A.G. (2009). Clustering acceptance and hedonic responses to cassava noodles extruded from cassava mosaic disease resistant varieties. Afric. J. of Food Sci. 3(11):334-339

Official Methods of Analysis of AOAC International. (2000). Ed. 19

Oyegbami, T., Oboh, G., Omuseti, O. (2010). Cassava Processors awarenesss of occupation and environmental hazards associated with cassava processing in south Western Nigeria. Africa J. of Food, Agric. and Nutri. Dev. 10(1): 1982-2000.

Prakash, Om and Kumar Anil (2013). A historical review and recent trends in solar drying systems. Int. J. of Green Energy. 10(7):690-738.

Prakash, Om & Kumar Anil (2017). Solar drying Technology, Green Energy and Technology. Springer Nature Singapore Pte Ltd. pp 89-175

Purandare, P., Bhong, M., Kulkarni, A., Mandar, M. (2013). Experimental analysis of recirculation type Solar dryer. Int. J. of Recent Sci. Res. 4(2):1175-1180

Rathore, N.S., Panwar N.L. (2010). Experimental studies on semi cylindrical walk-in type solar tunnel dryer for grape drying. Applied Solar Energy. 45(4):269-273

Sethi, V.P., Arora, S. (2009). Improvement in greenhouse solar drying using inclined north wall reflection. Solar Energy. 83(9):1472–84.

Sevda, M.S. and Rathore, N.S. (2010). Performance evaluation of the semi cylindrical solar tunnel dryer for drying handmade paper. J. of Renewable and Sustainable Energy. 2(1):1–18

Singh, S.P., Shrivastava, V., Kumar, A. (2018). Recent developments in Greenhouse solar drying: A Review. Renewable and sustainable energy reviews. 82(3):3250- 3262

Sonaye1, S.Y. and Baxi, R. N. (2012). Particle Size Measurement and Analysis of flour. Int. J. of Eng. Res. and Applications. 2(3): 1839-1842

Takrama, J.F. and Adomako, D. (1996). Raw Cocoa Processing in Ghana. Cocoa Research Institute of Ghana, New Tafo, Ghana. CRC press. pp 12-19

Tefera, A., Endalew, W., Fikiru, B. (2013). Evaluation and demonstration of direct solar potato dryer. Livestock Res. for Rural Dev. 25(12):207-223

Thompson, S.S., Miller, K.B. and Lopez, A.B. (2007). Cocoa and Coffee. Food Microbiology Fundamentals and Frontiers. ASM Press, Washington DC. pp 721-733

Tiwari Anupam. (2016). A Review on Solar Drying of Agricultural Produce. J. of Food Process Technol. 7(9): 623-636

Togrul, I.T. and Pehlivan, D. (2002). Mathematical modelling of solar drying of apricots in thin layers. J. of food Eng. 55(3):209-216

Vijayan, S., Arjunan, T.V., Kumar, A. (2017). Solar drying technology. Springer. pp 3-38

Vishal, D., Laxmikant, Y. and Avadhesh, Y. (2013). The Effect of Tilt angle on the Performance of Evacuated Tube Solar Air Collector: Experimental Analysis. Int. J. of Eng. Sci. and Technol. 5(4):100-110.

Wood, G.A.R., Lass, R.A. (1985). In Cocoa; from harvest to Store. Longman Scientific and Technical: New York, USA. pp 444–504.

Yang, X., Xu, W., Ding, J. and Zhao, Y. (2006). "Theoretical and Experimental Studies on Low Temperatures Adsorption Drying of Fresh Ginger". J. of Thermal Sci. 15(1):71-78.

Yashwant, K., Soumitra, T., Seema, A.B. (2015). Drying and excellent method for food preservation. Int. J. of Eng. studies and Technical Approach. 1(8):1-17

Zomorodian, A. A. and Dadashzadeh, M. (2009). Indirect and mixed mode solar drying Mathematical Models for Sultana grape. J. of Agric. Sci. and Technol. 11: 391-400

APPENDIX 1

Baseline Average Temperature & Relative humidity of Greenhouse type solar dryer and Open Sun

		GTSD		OSD	
Days	**Time (h)**	**Temperature (°C)**	**Relative Humidity (%)**	**Temperature (°C)**	**Relative Humidity (%)**
1	6:00	29.2	70	26.3	83
	9:00	31.4	58	30.9	67
	12:00	55.2	28	37.5	42
	15:00	50.1	39	30.6	63
	18:00	31.6	74	27.6	80
2	6:00	28.4	72	27.2	82
	9:00	29.9	58	30.3	70
	12:00	59.4	28	35.4	44
	15:00	50.7	37	29.2	68
	18:00	33.1	80	28.4	81
3	6:00	29.1	74	28.0	82
	9:00	33.2	60	31.1	69
	12:00	57.4	28	35.5	44
	15:00	52.0	40	29.3	64
	18:00	33.3	79	29.0	80
4	6:00	29.4	70	27.8	80
	9:00	33.1	58	30.2	72
	12:00	58.2	28	35.2	49
	15:00	49.4	39	30.1	69
	18:00	32.3	74	29.6	79
5	6:00	28.7	73	26.5	83
	9:00	32.3	59	30.5	70
	12:00	60.3	30	34.3	50
	15:00	55.2	40	29.3	72
	18:00	30.0	74	29.4	83
6	6:00	27.4	73	28.2	84
	9:00	29.2	58	30.4	80
	12:00	53.4	31	33.3	64
	15:00	47.4	43	29.7	78
	18:00	28.1	80	28.4	84
7	6:00	29.3	80	28.1	80
	9:00	31.3	65	29.0	79
	12:00	58.1	32	32.4	69
	15:00	52.2	40	29.6	80
	18:00	30.9	83	28.8	83
	6:00	28.4	73	27.5	79
	9:00	29.9	58	29.9	75

8	12:00	59.4	28	35.1	70
	15:00	30.7	39	29.6	65
	18:00	28.4	77	28.4	81
9	6:00	32.2	72	29.3	77
	9:00	55.7	59	29.9	70
	12:00	50.3	29	30.4	66
	15:00	32.4	37	32.5	63
	18:00	29.1	79	29.5	79
10	6:00	30.2	74	27.3	80
	9:00	57.7	60	29.5	77
	12:00	50.1	28	30.9	65
	15:00	32.3	40	31.2	63
	18:00	28.4	79	28.2	78
11	6:00	30.4	74	28.8	83
	9:00	32.4	62	29.5	80
	12:00	44.8	44	30.0	68
	15:00	29.1	56	31.2	69
	18:00	29.1	84	29.4	80
12	6:00	30.4	74	29.0	80
	9:00	58.9	63	30.9	79
	12:00	50.2	29	34.2	62
	15:00	29.4	42	30.1	60
	18:00	29.4	79	29.2	79
13	6:00	30.1	74	27.6	79
	9:00	32.1	61	29.8	74
	12:00	57.3	29	30.2	70
	15:00	50.2	44	31.5	67
	18:00	31.1	79	29.5	79
14	6:00	29.2	70	28.6	83
	9:00	30.4	58	29.9	76
	12:00	53.4	27	31.1	57
	15:00	47.2	40	28.7	70
	18:00	27.6	77	28.4	79

APPENDIX 2

Moisture content variation of cassava

Time (h)	Moisture Content (% ± SD)			
	Open Sun slices	**Open Sun chunks**	**Solar Slices**	**Solar chunks**
0	62.149 ± 0.825	62.149 ± 0.825	62.149 ± 0.825	62.149 ± 0.825
12	53.558 ± 2.070	61.579 ± 1.967	21.812 ± 2.894	47.368 ± 1.971
24	49.186 ± 3.304	61.986 ± 2.585	30.378 ± 1.554	53.061 ± 2.403
36	31.261 ± 2.305	32.517 ± 2.165	16.810 ± 0.528	12.829 ± 0.740
48	25.360 ± 1.176	33.628 ± 2.725	14.414 ± 0.159	30.398 ± 0.749
60	10.888 ± 1.065	23.965 ± 0.589	12.297 ± 0.303	29.157 ± 0.356
72	17.135 ± 3.560	23.809 ± 2.257	13.889 ± 2.232	28.757 ± 1.124
84	17.135 ± 1.739	21.082 ± 1.664	13.641 ± 3.440	15.325 ± 2.315
96	11.441 ± 0.984	21.802 ± 2.448	14.002 ± 2.421	31.861 ± 1.938
108	12.19 ± 0.710	17.766 ± 2.691	11.035 ± 2.564	20.781 ± 2.828
120	10.287 ± 1.107	18.288 ± 0.374	11.557 ± 1.883	14.635 ± 0.866
132	12.589 ± 0.308	11.854 ± 0.658	7.225 ± 0.266	11.882 ± 1.176
144	6.586 ± 0.325	11.193 ± 0.324	7.781 ± 1.987	11.934 ± 0.806
156	9.078 ± 0.227	11.159 ± 0.099	7.779 ± 2.030	11.294 ± 0.801

APPENDIX 3

Drying rates of Cassava (basis; initial moisture and 12 hour drying intervals)

	Drying rate (g / g h)			
Time (h)	**(Open Sun slices)**	**(Open Sun chunks)**	**(Solar slices)**	**(Solar chunks)**
0				
12	0.716	0.048	3.361	1.232
36	0.858	0.823	1.259	1.370
60	0.854	0.636	0.831	0.550
84	0.604	0.489	0.577	0.557
108	0.480	0.411	0.473	0.383
132	0.421	0.381	0.416	0.381
156	0.341	0.327	0.349	0.326

APPENDIX 4

Moisture content variations of cocoa beans

Time (h)	Moisture Content (% ± SD)	
	Solar cocoa	**Open sun cocoa**
0	53.340 ± 0.678	53.340 ± 0.678
12	55.472 ± 1.267	56.834 ± 2.315
24	55.650 ± 2.603	60.285 ± 0.679
36	49.110 ± 3.784	55.931 ± 0.577
48	49.446 ± 1.228	58.283 ± 0.224
60	35.793 ± 3.602	42.674 ± 3.563
72	36.003 ± 3.088	44.482 ± 4.390
84	28.263 ± 2.784	35.348 ± 5.376
96	28.630 ± 2.194	36.743 ± 2.003
108	17.628 ± 2.186	27.800 ± 3.036
120	17.990 ± 1.013	28.001 ± 0.238
132	10.223 ± 0.310	14.874 ± 0.231
144	10.370±0.221	15.504 ± 0.909
156	7.302 ± 0.339	9.350 ± 0.162
168		9.626 ± 0.342
180		7.495 ± 0.544

APPENDIX 5

Drying rates of cocoa beans (basis; initial moisture and 12 hour drying intervals)

Time (h)	Drying rate, (g / g h) (Solar cocoa)	Drying rate, (g / g h) (Open sun cocoa)
0		
12	0.239	0.126
36	0.182	0.121
60	0.228	0.260
84	0.092	0.109
108	0.102	0.083
132	0.059	0.099
156	0.020	0.039

APPENDIX 6

Colour Determination of dried Cassava flour samples

Sample	**L***	**a***	**b***
GTSD slices flour	88.03 ± 0.03	0.30 ± 0.02	10.95 ±0.18
GTSD chunks flour	80.89 ± 0.04	1.18 ± 0.01	14.44 ±0.02
OSD slices flour	85.75 ± 0.01	0.65 ± 0.00	9.23 ±0.03
OSD chunks flour	83.23 ± 0.03	-1.03 ± 0.02	12.88 ±0.03

APPENDIX 7

Dried Cassava flour Particle Size Distribution

Sieve size	GTSD Slices flour	GTSD chunks flour	OSD slices flour	OSD chunks flour
		Retained (%)		
1250 µm	9.8	10.9	9.3	11.1
850 µm	8.7	10.7	8.4	10.9
710 µm	8	9.8	7.8	9.5
425 µm	7.6	8.2	7.6	7.8
300 µm	7.4	6	7.1	5.8
250 µm	6	4.4	5.5	4.1
150 µm	4.2	3.3	3.3	3.5
100 µm	3.1	3.2	2..8	3.0
Cumulative passing	54.8	56.5	51.8	55.7

APPENDIX 8

Pasting Properties of dried Cassava Chips and the drying system

Sample	Gel Temp	Peak Viscosity	Viscosity @ 92C	92H	Viscosity @ 62C	Viscosity @ 62H	Breakdown	Setback
GTSD slices	68.6	1195	1126	512	684	720	681	169
GTSD chunks	68.6	1179	1006	436	567	607	742	129
OSD slices	69	1113	1112	522	654	680	590	129
OSD chunks	69.2	1144	1133	533	621	654	609	86

APPENDIX 9

NOMENCLATURE

k, c, a − Mathematical model constants

L_v − latent heat of water vaporisation $(\frac{J}{kg})$

$\frac{dm}{dt}$ − Mass flow rate of water evaporated (kg/s)

h_c − surface heat transfer coefficient (J/sm^2K)

S_p − surface area of the product (m^2)

T_a − drying air temperature (℃)

T_p − product temperature (℃)

h_m − mass transfer coefficient (J/hm^2Pa)

R − Reynolds number

Nu − Nusselt number

Ra − Rayleigh number

Gr − Grashoff number

D − diametre of the product (m)

v^2 − kinematic viscocity of air

β − coefficient of thermal expansion

g − acceleration due to gravity

T_∞ − the quiescent temperature (fluid temperature far from the surface of the object

L − vertical length of the product

P_w $/P_a$ − water vapour partial pressure

T_p − product temperature

P_{sat} − pure water vapour pressure

W_m − average absolute moisture

A_w − water activity

X − moisture content

Subscripts of X

cr - *critical*

eq - *equivalent*

f - *final*

o - *initial*

r - $ratio$ 7