MODELING OF DRYING COCOA BEANS *(Theobroma cacao l)* AND QUALITY EVALUATION UNDER OPEN SUN AND SOLAR DRYER

By

OLABINJO, Oyebola Odunayo
(AGE/95/5770)

A THESIS IN THE DEPARTMENT OF AGRICULTURAL ENGINEERING, SUBMITTED TO THE SCHOOL OF POSTGRADUATE, FEDERAL UNIVERSITY OF TECHNOLOGY, AKURE

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF MASTER OF ENGINEERING (M.ENG.) IN AGRICULTURAL ENGINEERING (CROP STORAGE AND PROCESSING OPTION), FEDERAL UNIVERSITY OF TECHNOLOGY ,AKURE.

NOVEMBER, 2010.

CERTIFICATION

This is to certify that this project was carried out by OLABINJO Oyebola Odunayo (AGE/95/5770) and submitted to the Department of Agricultural Engineering, Federal University of Technology, Akure in partial fulfillment of the requirement for the award of Master of Engineering (M.Eng) in Agricultural Engineering (Crop storage and processing Engineering Option).

It is also to the best of my knowledge that this work has not been submitted elsewhere for the purpose stated above.

------------------------------------	------------------------------------
Dr. J. O. Olajide Project Supervisor	Prof. L. A. S. Agbetoye Head of Department
30-11-2010 Date	6/12/2010 Date

DEDICATION

This project is dedicated to **God Almighty Father** and to my father in the Lord, **Prophet/ Evangelist Samson Oluwamodede.**

ACKNOWLEDGEMENT

My sincere and unreserved gratitude goes to the great God of heaven and earth, the best teacher and custodian of knowledge, wisdom and power. I will praise him with all my heart and all that is within me.

I am very grateful to my supervisor, Dr.J.O.Olajide, who showed much generosity by making relevant materials available to me and for his professional advice and guidance at all times. Without his unflinching support, my efforts would have proved less fruitful. Thank you sir. God bless.

In getting to this stage of the programme, I have depended on the ability of some lecturers who have patiently and intelligently impacted the knowledge unto me. I registered my appreciation to all the lecturers in the Department. I must sincerely thank Engr. A.P.Olalusi and Mrs. Mogaji B.R. for your immeasurable assistance and support. Special thanks to Mrs. Akintokunbo, my sister in Christ, for her spiritual and kind support. You are all blessed.

The work could not have gotten this far without the support, motivation, inspiration, encouragement and patience of my darling husband, loving children Ebenezer,Daniel and Samuel . I so much appreciate you for your kind understanding and whole-hearted co-operation at all times. Your effective fervent prayers at all times provide me a dependable fortress and the required spiritual support.

ABSTRACT

In this study, thin layer drying experiments were conducted on fermented cocoa beans. An indirect natural convection solar dryer consisting of a solar collector and a drying cabinet was used. Drying under open sun was conducted at the same time for comparison. Loading rate of 2.97, 3.21 and 3.97g/cm^2 of fermented beans were examined under field conditions of Akure. The drying process took place only in the falling rate period. The drying data were fitted into thirteen (13) different thin layer mathematical models. The result showed that the Verma *et. al* model was found to be the most suitable model for describing the drying curve of the convective indirect solar drying process of cocoa beans with R^2 = 0.9562,x^2 = 0.0069,MBE = 0.0383 and RMSE = 0.0067.while, the Midilli and Kucuk model, best described the drying curve of fermented cocoa beans under open sun with R^2 = 0.9866, x^2 = 0.0024,MBE = 0.0078 and RMSE = 0.0023.

The result from the cut test showed that all the dried cocoa beans falls in the first grade cocoa standard on the international standard which indicates good quality cocoa beans for both solar dryer and sun drying. The chemical assessment test based on pH showed that the beans dried in free convectional indirect solar dryer were of superior qualities with pH values between 5.50-6.00 against the corresponding values of 4.50-5.00 obtained under open sun drying. Indirect solar dryer is recommended for farmer as it is a cheaper alternative in terms of cost and convenience.

TABLE OF CONTENTS

CHAPTER FOUR

CHAPTER FIVE

NOMENCLATURE

a, b, c, g,h,n	empirical constants in the drying models.
K, k_o, k_1	empirical coefficients in the drying models (s^{-1})
n	number of constants
N	number of observations
Me	Moisture content in equilibrium state (wet basis)
Mo	Moisture content at t=0 (wet basis)
Mt	Moisture content at t (wet basis)
MR	Moisture ratio (dimensionless)
MRexp	Experimental moisture ratio
MRpred	Predicted moisture ratio
R	Regression coefficient
RMSE	root mean square error
Time	(sec, min, and hour)
T^{amb}	ambient temperature
T_{abs}	absorber temperature
T_{dryer}	dryer temperature
X_2	chi square.
MBE	mean bias error
Rel.hum	Relative humidity
Glo rad	global radiation
Net rad	Net/absorber radiation

LIST OF FIGURES

LIST OF PLATES

LIST OF TABLES

CHAPTER ONE

1.1 Introduction

Agricultural and other products have been dried by sun and wind in the open air for thousands of years. The purpose is either to preserve them for later use, as in the case with food; or as an integral part of the production process as with tobacco and cocoa beans. Food drying or dehydration is one of the oldest methods of preserving food by preventing the growth and reproduction of microorganisms causing decay and minimizing many of the moisture-content which cause deterioration reactions. In an industrialized region, open air-drying has now been largely replaced by mechanized dryers, with boilers to heat the incoming air and fans to force it through at a higher rate. Mechanised drying is faster than open-air drying, uses much less land and usually gives a better quality product but the equipment is expensive and requires substantial quantities of fuel or electricity to operate.

Cocoa beans are the seed of a cocoa tree which is a tropical tree botanically known as "*Theobroma cacao L*". It is a native of Tropical central and South America, in the forests of the Amazon to Orinola and Tabasco in Southern Mexico (Opeke, 1982).It is grown mostly in the wet tropical forest climate which is within 20^0 of latitude of the equator at countries such as Cote d'Ivore, Ghana, Nigeria, Cameroun, Brazil, Equator, Papua, New Guinea, Indonesia and Malaysia. Upon harvesting of ripe cocoa pods, fresh cocoa beans are fermented in wooden boxes for 5-7days and dried immediately after fermentation until it reaches a safe moisture level of 7.5%(wet basis).Cocoa is relatively easy and inexpensive to process, thus it's adoption as a cash crop by small farm holders in West Africa. The best quality cocoa is produced from well processed and clean environment.

1.2 Economic Importance

It is one of the World's most important commodities grown on over seven million hectares. The cocoa cultivated lands are mainly located in tropical biodiversity hot spots. It acts as a source of foreign exchange earnings for Ghana, Nigeria, Ivory Coast and Brazil. The basic use of cocoa bean is to manufacture chocolate, chocolate sweet, cocoa powder used for covering ice-cream, biscuits, cakes and other confectionaries to increase their acceptability to the public. The cocoa powder is mainly used as a drink, as a flavouring agent and in the manufacturing of cocoa-butter.

1.3 Importance of the Study

Drying is a process of moisture removal due to simultaneous heat and mass transfer for the purpose of preservation. Drying can be done either by traditional/natural sun drying or industrially through the use of solar or artificial hot air drying.

Open /Natural sun drying is still the most common method used to preserve agricultural products in most tropical and sub tropical countries.However,being unprotected from rain, wind borne, dirt and dust infestation by insects, rodents and other animals, products may be seriously degraded to the extent that some becomes inedible and resulted in loss of food quality. Some of the problems associated with open sun drying can be solved through the use of a solar dryer and it comprises of a collector, a drying chamber and sometimes a chimney (Madhlopa & Ngwalo, 2007).

Solar drying systems improve the traditional open-air drying system in many outstanding ways by lowering the costs of drying, improving the quality of the products and reducing post harvest losses of about 50 to 60% due to spoilage. Solar dryer can reduce crop losses and improve the quality of dried product significantly as compared with the traditional drying method (Muhlbauer, 1986).

Drying of cocoa is usually carried out using natural sun drying and artificial hot air techniques. The selection of drying technique largely depends on the production scale and affordability in terms of cost. Presently, sun drying is still the most widely used method especially by cocoa small holders due to its simplicity low cost set up and requires only direct sunlight which is renewable and abundant. It was also reported that sun dried cocoa beans have better flavour quality and less acidic due to its gentle drying process (Jinap,1994) on the other hand, artificial hot air drying method is normally associated with beans of weaker flavour quality, higher acidity, insufficient browning, smoke contamination and case hardening (Donald *et.al* 1981)Studies of the modeling of cocoa drying are relatively scarce and only few published literatures are available .Mathematical modeling of the cocoa drying process has been reported mostly in hot air drying under continuous operation(Donald *et.al* 1981;Fotso *et.al* 1994;Wan *et.al* 1996;Hil,2004).However, there is no report on modeling of the thin layer drying kinetics of cocoa beans under open sun and in solar dryer.

1.4 Objectives of the Study

The main objective of this project is to determine mathematical models that can be used to predict the drying characteristics of cocoa beans and investigate some quality attributes. The specific objectives are to:

a. conduct thin layer drying experiments on cocoa beans under open sun and in solar dryer.
b. fit the experimental data to existing mathematical models in order to determine an appropriate drying model for cocoa beans using relevant statistical methods.
c. compare some quality attributes of cocoa beans (appearance, cut test and pH) under open sun and in solar dryer.

1.5 Scope of the Study

The study was conducted in the Meteorology Department of Federal University of Technology Akure, Ondo State of Nigeria. The ripe cocoa pods were broken and fresh cocoa beans were removed from the pods and fermented in a wooden box for seven days. The fermented beans were dried in a convective indirect solar dryer and under open sun. Microsoft solver was used to analyze the data from the experiment. The data obtained are fixed into thirteen different equation models using the sigma plot and Microsoft excel to get the best model that describes the drying kinetics.

1.6 Justification

Solar dryers have usage potential all over Nigeria because of its high insulation and sunshine duration. They can be used to reduce post harvest losses and improve the quality of dried product significantly as compared to the open sun drying. A critically important aspect of drying technology is mathematical modeling of the drying process. Modeling of drying process and kinetics is a tool for process control and necessary to choose suitable method of drying for specific product. Modeling is also essential for design engineers to choose the most suitable operating conditions in order to design appropriate drying equipment to meet the desired operating conditions.

CHAPTER TWO

2.1 Origin of Cocoa

The genius Theobroma originated millions of years ago in South America and to the East of the Andes. Theobroma has divided into twenty –two (22) species of which *Theobroma Cacao* is the widely known. Archaeological evidence in Coast Rica indicates that Cacao was drunk by the Maya traders as early as 400 BC. The Aztec culture, dominant in Meso America from the fourteenth Century to the Conquest, placed much emphasis on the sanctity of Cacao. Cocoa was introduced to Fernando Po (now in Equatorial Guinea)by a sierra Leonean named William Pratt around 1840.For many years cocoa production was confined to the Western hemisphere. Cocoa plantation can be established by sowing the seeds or the cuttings in a special propagating bin in a nursery. The seed will germinate in 7 to 10 days and should be provided with shades. The seedlings are transplanted into a well-prepared field after about 4 to 5 months, when the rains are regular and steady (Wood 1975, Opeke, 1982).

2.1.1 Importance of Cocoa

Cocoa was the foremost Nigerian Foreign exchange earner before the advent of crude oil and its current second place position remains unchallenged. A whole cocoa pod is made up of about 56% husk, 42% beans and 2% mucilage or sweetens, while the testa of the bean is about 1% (Opeke, 1982) and almost every part of cocoa pod is useful from the husk to the nib.

More than a millennium after its discovery, chocolate is now a big business. The USA alone, the world's biggest consumer, consumes between 1 to1.4 million tonnes of chocolate every year, and the global trade in confectionery of which chocolate has the lion's share, is estimated at about US$ 80 billion per year.

Table 1 Uses of Cocoa beans

PRODUCTS	USES
Cocoa shell/dust	Livestock feeds, local manufacture of black soap, black Polish and fertilizer
Cocoa powder	Instant cocoa based food drinks, chocolate, dairy feeds, Bakery, biscuits confectionery.
Cocoa cake	Livestock feed enrichment and flavour agent.
Cocoa butter	Chocolate, biscuit, confectionery, cosmetics, pharmaceuticals manufacture.
Cocoa Liquor	Eating chocolate, sugar coated sweet
Cocoa Mucilage (Sweetens)	Cocoa sweetens is bottled as soft drink in Brazil.

Source: - Akinsoyinu &Adeloye (1987), Ahankorah *et.al* (1987)

2.1.2 Cocoa in Africa and Nigeria

Cocoa has become a vital export crop for many countries, particularly in West Africa, which produces over 65% of the world's cocoa. It is also a major foreign exchange earner for some Central and South American countries and for South and Southeast Asia. It is the bedrock of Ghana's economy and the most important of Nigeria's non-oil export (Wood, 1975).

It was introduced into Nigeria by Chief Squiss Ibamigo, who established the first plantation in Bonny, Rivers state in 1874, from the seeds he obtained from Fernando Po (Opeke 1982, Are and Gwynne-Jones, 1974, Wood, 1975.) Over 80% of all cocoa is produced by smallholder farmers. Cocoa is grown mainly by small holders in Nigeria particularly in Ondo State which accounts for about 60% of Nigeria's total output. It is the principal source of income for millions of such farmers, families and workers. It provides essential source of earning for the people and benefits the economy of the country. Cocoa is recognized to be environmentally friendly in that it can be grown in harmony in the environment in which it thrives.

Table 2 Cocoa Markets, Cocoa Production Statistics.

WORLD COCOA BEAN PRODUCTION ('000)

	2002/03	2003/04	2004/05	2005/06	2006/07 (Forecast)
World	3,232	3,651	3,446	3,731	3,388
Africa	2,234	2,658	2,438	2,666	2,347
Americas	500	445	439	439	431
Asia/Oceania	498	548	569	626	610
Africa					
West Africa (WA)					
Cameroon	152	160	190	173	175
Côte d'Ivoire	1,367	1, 550	1, 410	1,519	1,380
Ghana	498	736	591	740	582
Nigeria	178	174	206	190	165
Sub total (W/A)	2,195	2,620	2, 397	2,622	2,302
Other Africa	39	38	41	44	45
Total Africa	2, 234	2,658	2, 438	2,666	2,347
Americas					
Brazil	163	163	171	162	145
Ecuador	87	117	114	115	120
Other America	250	165	154	162	166
Total Americas	500	445	439	439	431
Asia/Oceania					
Indonesia	413	460	470	520	500
Malaysia	21	25	26	27	28
Other Asia	64	63	73	79	82
Total Asia	498	548	569	626	610

Sources: FAO, (2006)

2.2 Cocoa

The trees start to produce fruits at about 3 to 4 years old, depending on the variety. The cocoa fruit, commonly called a pod is botanically a berry. It varies in size, colour and oval shaped pods,8 to 14 inches long, ranging in colour from yellow or green to red or violet depending on the varieties. It takes 5-6 months for the pods to grow and ripen; Plate 1 shows the picture of a mature tree with ripe cocoa pods. It is made up of five united carpels and contains an average of 20 to 40 seeds (beans). The beans are embedded in a mass which could be white, pinkish or mature tree with ripe cocoa pods. It is made up of five united carpels and contains an average of 20 to 40 seeds (beans). The beans are embedded in a mass which could be white, pinkish or brownish. The beans are flat or rounded, white, brownish or purple, sweet or bitter and each is about 2cm or more in diameter.

Plate 1 Mature Cocoa tree with ripe Pods

2.3 Processing of Cocoa beans

Cocoa bean is about 20-30mm long, flattened, chocolate brown in colour. It consists of two chocolate brown cotyledons. Cocoa beans were processed and handled in a special way apart from the other oilseeds. Cocoa bean is the only oilseed that is pre-processed by the farmer before been sold to the eventual processor.

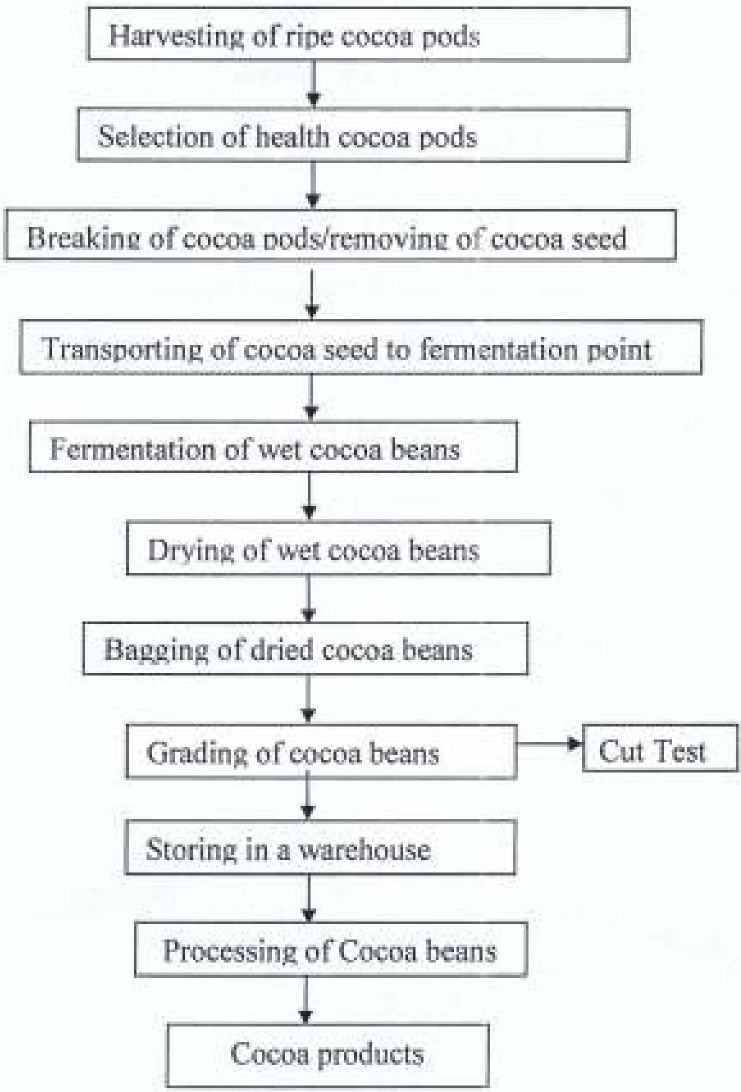


Figure 1 Flow chart of cocoa processing.

2.3.1 Harvesting of ripe Cocoa Pods

It is the starting point in the processing of Cocoa. Only ripe pods should be harvested, inclusions of unripe and over-ripe pods increase the number of flat and germinated beans in the finished cocoa (Kenten, 1964). Harvesting is the removal of the ripe pods from the trees. It takes Cocoa pods from 110-130 days to reach maturity. The harvesting of pods is carried out by using sharp hook, sharp knife tied to a long or short pole named Go-To-Hell. It is designed to cut both ways with either an upward or a downward thrust. Other important tools that are needed for pod harvesting are sharp cutlasses or machetes for removing pods that are within the reach and baskets or any container for packing the harvested cocoa pods (Wood, 1975, Opeke, 1982) .It is the breaking of pods to extract the wet beans. The Cocoa pods are broken to remove the Cocoa beans. Break pods with blunt object (wooden).Avoid use of cutlass or sharp objects to prevent cutting or damaging the beans inside the pods as shown in plate 2. The beans covered with sticky mucilage, are either removed by hand or with the point of a cutlass (Wood, 1975) reported that a man can harvest about 1,500 pods a day. The following must be set aside during the breaking of pods:-Beans from damaged pods, dry or diseased beans, beans from black pods, germinated or germinating beans and small or unmatured beans. Breaking of pods must be done immediately after harvesting.

Plate 2 Cocoa pods that have been broken with the seed.

Plate 3 Breaking of harvested ripe cocoa pods at the right time.

2.3.2 Fermentation of Cocoa beans

Fermentation involves the conversion of sugar to alcohol and alcohol to acetic acid and it lasts from four to seven days. Cocoa contains mucilage around the beans which is removed by fermentation. The main purpose of fermentation of cocoa beans is to develop the chocolate flavour and aroma, and to get rid of the pulp around the beans. Besides fermentation help to kill the embryo and stop germination and to loosen the coat from cotyledon so that the beans can be easily and properly dehulled (Wood, 1975).It is basically a heating process but requires an adequate aeration to prevent the temperature from rising too high. During the first day of fermentation, the adhering sugary pulp becomes liquid and drains away with the temperature rising steadily and the sugars in the pulp are first converted to alcohol by the activities of yeast (saccharomyces spp) and finally iodized into acetic acid by a bacteria (Actobacter spp).The embryo of the beans are killed (destroyed) by the penetration of alcohol and acetic acid, thereby resulting in the chocolate brown colour. The factors that influence the course of fermentation are the ripeness of the pod, pod diseases, type of cocoa, the interval between harvest and pod-opening, the batch size, the climate, the amount of mixing, the amount of aeration and the seasons(kenten,1964,Wood,1975). The correct fermentation and drying is of vital importance to the quality of cocoa products and no subsequent processing of the beans will correct for a bad practice and undesirable elements including pulps and broken husk must be removed from freshly extracted beans in order to produce good quality cocoa beans. A good flavour in the final cocoa or chocolate is related closely to good fermentation but if drying after fermentation is retarded, mould develop and these impart very unpleasant flavour even if fermentation has been carried out correctly and Plate 4 shows different fermentation methods.

i. Heap method
ii. Baskets method
iii. Sweatbox method
iv. Tray method

Plate 4 Different fermentation methods.

2.4 Drying

Drying of Agricultural products is an important unit operation under post harvest phase. It is a convection process in which moisture from product is removed. It refers to removal of moisture from grains and other products to a predetermine level or very low levels. Drying is a process of moisture removal due to simultaneous heat and mass transfer for the purpose of preservation. It is a thermo-physical and physic-chemical operation by which excess moisture from a product is removed. Drying prevents occurrence of undesirable changes due to microbial activity. It can be done either by traditional/natural sun drying or industrially through the use of solar or artificial hot air drying. Although preservation is the primary reason for drying, it also lowers the product mass and volume. The reduction in a mass and volume improves the efficiency of packing, storing and transportation. Plate 5 shows the diagram of open sun drying in a clean environment Solar dryers could be an alternative to the hot air and open sun drying methods especially in locations with good sunshine during the harvest season. In solar dryers, the product does not include any kind of preservatives or other added chemicals and the product is not exposed to any kind of harmful electromagnetic radiation of electromagnet poles. Properly designed solar dryer not only meet the particular drying requirements of crops of interest but also increase energy efficiency and conservation in an agricultural management practices. Some of the problems associated with open sun drying can be solved through the use of a solar dryer. It comprises of a collector, a drying chamber and sometimes a chimney (Madhlopa *et al,* 2007).

Plate 5   Drying of fermented Cocoa beans under clean surrounding.

2.4.1 Importance of drying

i. Drying is a simple, low cost way to preserve food that might otherwise spoil.
ii. Drying of agricultural products to optimum moisture content results in safe storage of products over a longer period and thus prevents fermentation or the growth of moulds.
iii. It also slows the chemical changes that take place naturally in foods, as when fruits ripen.
iv. Storage of products after drying makes products available during off seasons. Selling of products in off season would fetch additional income to growers as prices remain higher during these periods.
v. Also, drying brings about substantial reduction in weight and volume, minimizing, packaging, storage and transportation costs [Okons *et.al,* 1992].

The types of loss generally caused by fungi are:-

a. Reduction in the germination rate of the seed.
b. Discolouration, which reduces value of foods for many purposes.
c. Development of mustiness or other undesirable odours or flavours.
d. Chemical changes that render food undesirable or unfit for processing.
e. Production of toxic products, known as mycotoxins, some which can be harmful if consumed.

2.4.2 Principles of drying

At harvest, most grains contain more moisture than what is safe for prolonged storage, because many fungi grow rapidly in warm moist conditions. Thus, any grain stored for future use must be dried shortly after harvest to prevent the growth of destructive fungi. In general grains will not be completely dried since they are hygroscopic. Food preservation is very important for food safety and security. Unsuitable preservation and storage methods cause losses of food which range from 10% to 30% for Cereals and 50% to 70% for fruits (Yaldyz & Ertetny, 2001).

2.4.3 Mechanism of drying

There are two basic phenomena generally accepted to be involved in drying process of agricultural products. They are.

A. Evaporation of moisture from the surface

It can be considered that moisture evaporates from a wet surface in the same way as it evaporates from a free water surface. As long as the surface remains completely wet, the rate of evaporating is constant. In this case the rate of drying is the same as those affecting the rate of evaporation from a free water surface and the factors are its temperature and humidity. The rate of evaporation is proportional to the difference between the saturation vapour pressure of the surface temperature, and the partial vapour pressure of the water in the adjacent air, P_a. The vapour pressure product, from the surface p_s,increases with increasing air temperature at constant humidity whereas pa increases with humidity at any given temperature. To obtain fast drying, large vapour pressure difference must occur. In practical terms, the warmer the drying air the greater the vapour pressure differences $\{P_s - P_a\}$ and hence the greater the rate of evaporation.

Much of the heat necessary for evaporation of moisture from a particle is supplied from the air by convection but conduction and radiation of heat to the particle can also be important. Material dried on metal trays for instance, can receive appreciable heat via conduction through the tray bottom.

B. Migration of moisture

Moisture migration refers to the movement of moisture from the interior of the particle to the surface. The migration of moisture from the internal structure of the food particle is governed by two mechanisms: diffusion and capillary flow. The rate of moisture migration is in turn affected by the temperature of the food particle, its moisture content and the size of the particle .The higher the temperature of the food, the greater will be the rate of moisture migration. There will be a continuous decrease in the moisture content of the food particle hence, a decrease in the rate of moisture migration. The rate of moisture migration will also increase with decrease in size of particle. (ILO, 1986).

From basic Physics it can be realized that temperature of a particle, its moisture content and the physical dimensions of the particle are the most important factors affecting the rate of moisture migration but the internal structure and composition of the materials are also important.

The general equation for diffusion of liquid through a porous solid i.e.

$$\frac{dMc}{dt} = \frac{Dd^2Mc}{dx^2} \quad \text{--} (1)$$

Where

Mc= moisture content on dry basis
T = time , D = diffusion coefficient
x = distance from the particle surface.

This equation shows that the change in moisture content with time is proportional to the change in moisture gradient across the particle from interior surface. In practical terms, it can be appreciated that the rate of drying decreases with particle size.

2.4.4 Heat transfer in drying

The rate of drying are generally determined by the rates at which heat energy can be transferred to the water or in order to provide the latent heats, though under some circumstances the rate of mass transfer (removal of water) can be limiting. All three of the mechanisms by which heat is transferred conduction, radiation and convection may enter into drying. The relative importance of the mechanisms varies from one drying process to another and very often one mode of heat transfer predominates to such an extent that it governs overall process. As an example, in air drying the rate of heat transfer is given by

$Q = H_s A(T_a - T_s)$--(2)

Where

Q = Heat transfer rate in Js^{-1} H_s= Surface heat transfer coefficient $JM^{-2}S^{-1}{}^{\circ}C^{-1}$
A =Area through which heat flow is taking place, m^2
T_a=Air temperature and T_s=Drying temperature of the surface, °C

2.5 Drying rates and patterns

Two drying rates or periods are identified during the drying process: Constant rate drying and falling rate drying.

2.5.1 Constant-rate drying period

When food is placed in a drier, there is a short initial setting down period as the surface heats up to the wet-bulb temperature (A-B in Figure 2(a)). Then, drying commences. Provided water evaporates from the food surface at the same rate at which it moves from the interior of the food, the surface remains wet. This phenomenon is known as the *constant rate period.* This continues until certain critical moisture content, CMC, is reached (B-C in Figure 2 (a) and (b).

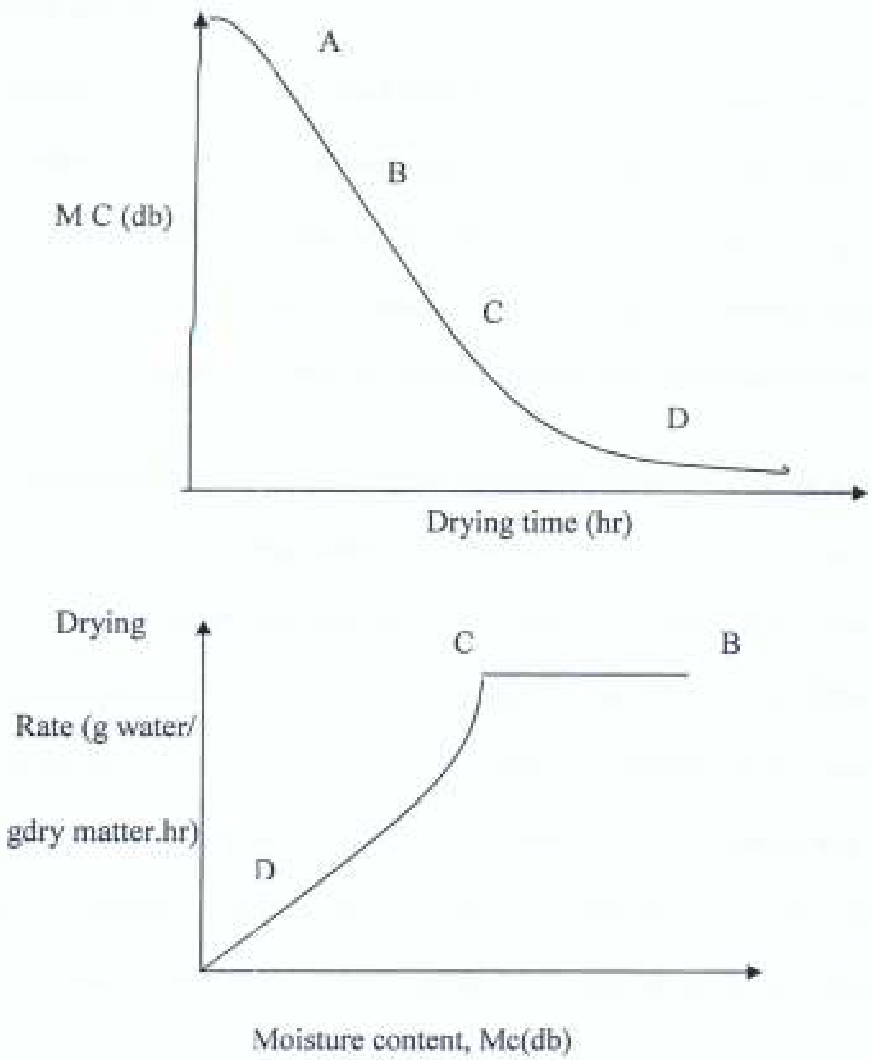


Figure. 2 (a) and (b) Drying curves. Temperature and humidity are constant.

The surface temperature of the food remains close to the wet-bulb temperature of the drying air until the end of constant-rate drying period, due to the cooling effect of the evaporating water. In reality, different areas of food surface dry out at different rates as a result of non- isotropic properties of food. Overall, the drying rate declines gradually towards the end of the constant-rate period. The magnitude of the rate of drying during constant rate periods depends on the area of crop that is exposed. At this constant stage, the food will dry as rapidly as the air can remove the moisture .This period is known as the Constant rate drying period. (ILO, 1986).

2.5.2 Falling-rate drying period:

When the moisture content of the food falls below the critical moisture content, the rate of drying slowly decreases until it approaches zero at the equilibrium moisture content, i.e. the food comes in equilibrium with the drying air. This is called the *falling rate period*. Non-hygroscopic foods like green pepper (Akpinar and Bicer, 2008), strawberry (Ibrahim, 2007) have a single falling period(C-D in Figure 2 (a) and (b) whereas hygroscopic foods have two or more periods.

During the falling period(s) the rate of water movement from the interior to the surface falls below the rate at which water evaporates to the surrounding air. Therefore, the surface dries out assuming that the temperature, humidity and air velocity are constant. If the same amount of heat is supplied by the dry-bulb temperature of the drying air. Therefore, most of the damage to food during drying occurs in the falling rate period. Most heat transfer is by convection from the drying air to the surface of the food, but there is also heat transfer by conduction from the tray on which the food is placed on and also by radiation. The calculation of heat transfer is complex; therefore drying models are simulated to explain the drying of foods and design food drying machines.

This immediately follows constant rate drying when all the free surface water and the water of saturation are completely removed. The product largely controls the falling rate period and it involves the movement of moisture within the material to the surface by diffusion and removal from the surface. This period (Falling rate) is described by

$$\frac{Dm}{dt} = vnPs\,(M - Me) \text{------------------------------} (3)$$

Where

$\frac{dm}{dt}$ = drying rate and n–constants depending on the crop

v - Air velocity, P_s- Saturated vapour pressure.

$M_r = \frac{M-Me}{Mo-Me}$ M_r –Moisture ratio, M -Moisture Content at Time (t)

M_o-Initial moisture content, M_e-Equilibrium moisture content.

2.6 Determination of drying constant for crops

Single layer drying, generally referred to as thin layer drying takes place according

$$\frac{Dm}{dt} = K\,(M - Me) \text{--} (4)$$

When intergrated it yields

$$\left(\frac{M-Me}{Mo-Me}\right) = e - kt \text{--} (5)$$

Where

K-drying constant for thin layer drying hr-1

T- drying time (hr)

M-average moisture content at anytime (%db).

M_o-Initial moisture content percent at any basis (%db)

M_e-Equilibrium moisture content percent by basis (%db)

The drying constant K can be expressed as

$$K = -\frac{1}{t}\, In\, \frac{M}{Mo} \text{--} (6)$$

2.6.1 Determination of moisture content

Moisture content (MC) of a substance is defined as the amount of water present in it. The amount of moisture in a product is given on the basis of the weight of water present in the product and is usually expressed in percentage. The information of moisture content is necessary because it tells us whether the product is suitable for safe storage or for any other processing job. There are several methods for determination of moisture content of agricultural products. Moisture content can be determined mainly by two methods,

1. Direct, also called primary methods: - the accuracy of direct method is high, hence this method is use by research workers. It is time consuming; such cannot be used in warehouses and in the field. Examples of direct method are (i) Air oven method, (ii) Vacuum-oven method and (iii) Brown-duvel fractional distillation method.
2. Indirect, also called secondary methods: - it involves the measurement of a property of the material which depends upon the moisture content. The moisture content is usually expressed on a wet basis for the indirect methods. All types of moisture meters fall under the indirect methods for moisture measurement. Examples of indirect method are (i) Electrical resistance method,(ii)Relative Humidity method

Moisture content, could be expressed as wet basis or dry basis

$$\text{Moisture content wet basis } (MC_{wb}) = \frac{\text{Weight of water in the product}}{\text{Weight of wet product}} * 100$$

$$MCwb = \frac{Ww}{Ww+Wd} * 100\% \text{------} (7)$$

$$\text{Moisture content dry basis } (MC_{db}) = \frac{\text{Weight of water in the product}}{\text{Bone dry weight of wet product}} * 100$$

$$MCdb = \frac{Ww}{Wd} * 100\% \text{------} (8)$$

The relationship between wet and dry basis moisture content is given by the following expression.

Moisture content, % (db) = $\frac{\text{Moisture content, (wb)}}{\text{100 - moisture content, (wb)}}$ *100 ------------------ (9)

Moisture content, % (wb) = $\frac{\text{Moisture content, (db)}}{\text{100 + moisture content, (db)}}$ *100------------------- (10)

Usually moisture content dry basis is greater than moisture content wet basis while MC_{wb} is used for commercial purposes and standard, MC_{db} is used for scientific purposes for drying products. It was considered that the weight loss equation was similar to moisture content equation form and its development .Weight loss was estimated using equation below (Verma *et al*, 1985) depending on weight changes of samples during the drying experiments.

$$M = \frac{Mt - Me}{Mo - Me} \text{---------------------- (11)}$$

2.7 Factors affecting the rate of drying

The major factors that affect the rate of drying of a foodstuff are enumerated by Bansal *et al*, (1990) as the physical and chemical properties of the product, i.e. shape, size, composition and moisture content. The geometrical arrangement of the product in relation to the heat transfer medium (e.g. thin layer drying, deep bed drying and e.t.c).

The process of drying food is affected by the following drying parameters:

i. Temperature of the drying air: the higher the temperature of the drying air, the more heat energy is transferred to the food; hence, the water vapour in the food is quickly removed (Mustafa *et al.*, 2009).
ii. Humidity of the drying air: the humidity of the drying air is influenced by the amount of water vapour removed from the food (as the drying process takes place), since as the food

is gradually dried, the surrounding air becomes humid. Hence, the drying air has high moisture content, so it becomes less effective to dry the food. Therefore, it is advisable to remove exhausted drying air through chimneys to great heights where it can no longer influence the drying air humidity.

iii. Flow direction and intensity (flow rate) of the drying air: if the drying air is in the direction of the food been dried the drying process is enhanced and the higher the drying air intensity (i.e. air velocity) the more water vapour is removed from the food.

iv. Area of exposed surface of the food particle: thin layer, wide surface foods are quickly and easily dried than deep bed, narrow surface food. Hence, thin layer of foods are used for experimental analysis to generate its drying model and optimization.

v. Composition and structure of the food: the structure and constituents of food has influence on the mechanism of moisture removal. For instance, the orientation of protein strands in meat allows more rapid moisture removal along its length than across the structure. Similarly, moisture is more easily removed from intercellular spaces than within cells. Therefore, rupturing cells by blanching or size reduction increases the rate of drying (Fellow, 1988).

2.8 Solar Energy

Solar energy is generally defined to include energy derived directly from sunlight as well as indirectly in the form of wind, waves, tides, ocean thermal gradients or as fuel from biomass and other petrochemical reaction products (Carneige & Pohl, 1980). Solar energy is the radiant energy produced in the sun because of nuclear fusion reactions. It is transmitted to the Earth through space by electromagnetic radiation in quanta of energy called photons, which interact with the earth's atmosphere and surface. The Earth receives 174 petawatts (PW) [about half the incoming solar energy] of coming solar radiation (insulation) at the upper atmosphere. At the periphery of the earth's atmosphere, the strength of solar radiation is $1367 w/m^2$ or about 2 $calories/min/m^2$ which are called solar constant. The intensity of energy actually available at the earth's surface is less than the solar constant because of absorption and scattering of radiant energy as photons interacts with the atmospheric particles.

The strength of the solar energy available at any point on the earth depends in a complicated but predictable way, on the day of the year, the time of the day and the latitude of the collection point (Rabiu, 2003b). The solar energy is vast abundant in the tropics because of the geographical location of the region. Furthermore the amount of solar energy that is collected depends on the orientation of the colleting object.

The continuity of life on earth hinges on solar energy, as it drives the atmospheric circulation, the heat flow that causes evaporation and rainfall, the ocean tides, and the photosynthesis of our food chain. All forms of energy used by humans except nuclear and geothermal energy are traceable to the sun. Man harnesses and uses solar energy in various forms. e.g. in the laundry process to dry wet clothes and in agriculture for the preservation of farm products. Man and animals owe their survival to solar energy technology, which can be adapted by fabricating solar dryers, solar cookers, solar panels, and other solar energy conversion device for the use of man.

2.9 Solar Dryer

Solar dryer is any device that uses solar radiation to remove moisture from a substance. It uses the energy of the sun to heat the air that flows over the food in the dryer. As air is heated, its relative humidity decreases and it is able to hold more moisture. Warm dry air flowing through the dryer carries away the moisture that evaporates from the surfaces of the food. Solar drying systems improve the traditional open-air drying system in many outstanding ways by lowering the costs of drying, improving the quality of the products and reducing post harvest losses of about 50 to 60 percentage due to spoilage. Solar dryer can reduce crop losses and improve the quality of dried product significantly as compared with traditional drying method (Muhlbauer, 1986)

2.9.1 Types of Solar dryer

Solar dryers fall into two broad categories namely active and passive dryers as shown in Figure 3. It can be further divided into direct and indirect models, a direct (passive) dryer is one in which the food is directly exposed to the sun's rays. In an indirect dryer, the sun's rays do not strike the food to be dried.

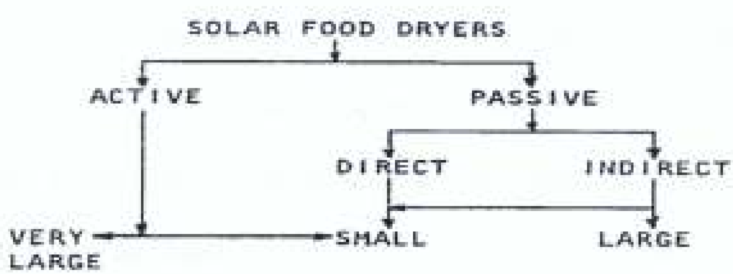


Figure 3 Breakdown of Solar food dryers. Source:-www.vita.org.

2.9.1.1 Passive Solar dryer

Passive solar food dryers use natural means (radiation and convection) to heat .They can be constructed easily with inexpensive, locally available materials. Direct passive dryers are best used for drying small batches of foodstuffs. Indirect dryers vary in size from small home dryers to large –scale commercial units. Passive dryers use only the natural movement of heated air. They can be divided into three sub-groups.

a. Direct dryers: - This is a dryer typically made up of a drying chamber (cabinet or box) covered by transparent cover or side panels made of glass or transparent plastic. The drying chamber is an insulated box with holes in the base and upper parts to allow air to enter and leave the box. The interior of the chamber is blackened to act as heat absorber. The food is placed or spread on perforated trays that allow air to flow through them.
b. Indirect dryers: - An indirect dryer is one in which the sun's rays do not strike the food to be dried. In this system, drying is accomplished indirectly by passing heated air through a solar collector into the chamber. Within the chamber, the food is placed on perforated trays that allow air flow through them. They exist as bin type, tunnels or continuous belt type.
c. Mixed mode dryers: - A Mixed-mode solar dryer can be grouped under passive dryers, as it combines both the direct and indirect type of dryers. It looked like an indirect dryer because of the separate solar collector, but there are transparent surfaces on the roof and Eastern side of drying cabinet that makes the direct aspect. Thus it can be used wholly either as direct or indirect, passive dryers can have their solar collectors directly combined with the drying chamber, and can equally have them separated. Some passive dryers use air heaters without any transparent surface.

2.9.1.2 Active dryer

Active dryers require an external means, like fans or pumps, for moving the solar energy in the form of heated air from the collector area to the drying bed. In active dryer, the solar –heated air flows through the solar drying chamber in such a manner as to contact as much surface area of the food as possible.

2.10 Review of works on studies of solar dryer.

The National institute of oceanography (1996), constructed a cabinet type solar dryer for rural women in coastal areas. The dryer consists of rectangular box, which is 100m long, 50 cm broad and 35 cm high, with a tilted upper lid. It has two special features; firstly, a nylon wick to collect and discharge condensed water, secondly, a detachable metallic hinge, filled in the middle of the cabinet. The result shows that there is a reduction in the drying time compared to conventional (open air drying).The efficiency of the cabinet dryer was about 10 percent.

Herbert *et.al* (1984) classified solar dryers into two broad categories; the first category is the dryer in which the sunlight is directly employed, which can further be divisible into three sorts; traditional drying racks in the open air, covered racks(protected against dust and insects) and drying boxes provide with insulation and absorptive material called cabinet solar dryer. The second categories are the dryers in which the sunlight is employed indirectly using a chimney where the drying air is warmed in a space other than that where the product is stacked. Also various sorts of construction are possible, the design can be provided with powered fans in order to optimize air circulation.

Bjorge (1998),in his review argued that food items dried in a solar dryer were superior to those subjected to open drying when evaluated in terms of taste, colour and moulds counts; thus improving food preservation. This translates into quality product that can be stored for extended periods at less cost while still providing excellent nutritive value.

Habou *et.al* (2003),carried out a comparative study of the drying rate of tomato and pepper using forced and natural convention solar dryers located and inclined at angle of latitude 10.33^0N(Bauchi,Nigeria).The two solar dryers were fabricated using the same material and were of same dimension. The drying chamber is also of dimension 0.9m x 0.54m x 0.25m, in which drying trays are placed., a fan is fitted, in order to aid the airflow out of the dryer, performance test showed that the percentage moisture removed from tomato and pepper are 93.74% and 91.11%respectively using forced convention drying at an average solar radiation of 449.38w/m2 while under similar sunshine condition the percentage moisture removed from tomato is up to 96.92% using natural convention drying. The forced convention drying time is only 64.23% that required for drying under natural convention.

Garba *et.al* (1997) in a bid to solve the problem of spoilage and preserved agricultural produce due to lack of suitable processing and preservation facilities, designed and constructed two passive solar dryers. These two dryers have similar collector area $0.93m^2$ and drying chamber area $0.96m^2$ as the essential component. The only different is that one of them has a rock bed heat storage system below the drying chamber. Food items like potato chips, tomato slices, meat cuts and onion slices were dried using these dryers.

2.11 Studies on mathematics modeling of drying systems

Thin layer drying equations are used to estimate drying times of several products and also to generalize drying curves. Several investigators have proposed numerous mathematical models for thin layer drying of many agricultural products. Most of the mathematical models used in the studies dealing with the thin layer drying are given in Table 2.3. Eiham *et al,* (2009) used Midilli and Kucuk in Table 2.3 to describe the drying curves of apples. Kongdej and Songchai, (2009) adopted the Henderson and Pabis model for describing the drying kinetics of steamed glutinous rice. Akpinar and Bicer (2008) used Logarithmic model to stimulate thin layer drying of long pepper for forced solar drying and Midilli and Kucuk model for natural sun drying .El-Beltagy *et al,* (2007) used Newton model to describe the solar drying curve of strawberry.

a. Moisture content

The amount of moisture content (MC) in a product is designated on the basis of the weight of water (i.e dry or wet basis).On dry basis (%) it can be calculated as follows (Ceylan *et al.*,2007; Haque & Langrish,2005; Saeed *et al.*,2006; Upadhyay *et al.*,2008):

$$MCwb = \frac{Ww}{Ww+Wd} * 100\% \text{--} (12)$$

And on wet basis (%) by the formula (Hall,1980;Rodrigues & Fernandes,2007;Simpson,1991)

$$MCdb = \frac{Ww}{Wd} * 100\% \text{--} (13)$$

The two ways of expressing moisture content are related by (Ekechukwu,1999; Hall,1980):

$$\text{Moisture content, \% (db)} = \frac{\text{Moisture content, (wb)}}{\text{100 - moisture content, (wb)}} *100 \text{ ------------------ } (14)$$

$$\text{Moisture content, \% (wb)} = \frac{\text{Moisture content, (db)}}{\text{100 + moisture content, (db)}} *100 \text{-------------------- } (15)$$

Table 3 Some thin layer drying equation.

Model name	Model equation	References
Newton	$MR = \exp(-kt)$	Ayensu,(1997);Togrul & Pehlivan,(2004); Upadhyay et al.,(2008);Mujumdar,(1987).
Page	$MR = exp(-kt^{n})$	Kaleemullah Kaleemullah & Kailappan,(2006);Saeed et al.,(2006);Senadeera et al.,(2003); Diamante and Munro (1993).
Modified page	$MR = \exp[-(kt)^{n}]$	Goyal et al.,(2007);Ceylan et al.,(2007);Sogi et al.,(2003); White,Bridges,Loewer & Ross (1978).
Henderson and Pabis	$MR = aexp(-kt)$	Kashaninejad et al.,(2007);Saeed et al.,(2006);Ozdemir & Devres,(1999); Zhang and Litchfield (1991).
Logarithmic	$MR = aexp(-kt) + c$	Babalis et al.,(2006);Celma et al.,(2007);Lahsasni et al., (2004);Yagcioglu,Degirmencioglu,and Cagatay (1999).
Two-term	$MR = aexp(-k_{0}t)\, bexp(-k_{1}t)$	Lahsasni et al., (2004);Rahman et al.,(1998);Wang et al.,(2007)., Henderson (1974).
Two-term exponential	$MR = aexp(-kt) + (1-a)\exp(-kat)$	Midilli & Kucuk, (2003);Sacilik et al.,(2006);Tarigan et al., (2007); Sharaf-Eldeen,Blaisdell,and Hamdy(1980).
Wang and Singh	$MR = 1 + at + bt^{2}$	Wang and Singh (1978).
Approximation of diffusion	$MR = aexp(-kt) + (1-a)\exp(-kbt)$	Wang et al., (2007);Yaldiz and Ertekin (2001);Togrul & Pehlivan (2002).
Modified Henderson and Pabis	$MR = aexp(-kt) + bexp(-gt) + cexp(-ht)$	Karathanos (1999).
Verma et al	$MR = aexp(-kt) + (1-a)\exp(-gt)$	Doymaz,(2005);Karathanos, (1999);Yaldiz &Ertekin,(2001); Verma,Bucklin,Endan,and Wratten (1985).
Midilli and Kucuk	$MR = aexp(-kt^{n}) + bt$	Midilli and Yapar (2002).
Thompson	$t = a\ln MR + b(In(MR))^{2}$	Thompson,Peart and Foster (1968).

b. Moisture Ratio (MR)

Moisture ratio is the ratio of the moisture content at any given time to the initial moisture content(both relative to the equilibrium moisture content).It can be calculated as (Ozbek &Dadali,2007;Shivhare *et al.*,2000;Thakor *et al.*,1999)

$$M = \frac{Mt - Me}{Mo - Me} \text{ --(16)}$$

c. Drying Rate (DR)

The drying rate can be expressed as (Ceylan et al.,2007;Doymaz,2007;Ozbek & Dadali,2007):

$$DR = \frac{Mt+dt-Mt}{dt} \text{ --(17)}$$

2.12 Statistical methods commonly used to determine Goodness –of Fit Statistics

Thin layer drying models were evaluated and compared by using statistical measures. The quality of the fitted models was evaluated .Some of the measures can be described as follows:

i. Coefficient of determination (R^2) :- It evaluates how well the model fits the data and commonly used as major statistic's. It is used by various authors to evaluate the drying models (Doymaz,2007;Panchariya *et al.*,2001;Saeed *et al.*,2006;Singh *et al.*,2006).

$$R^2 = \frac{\sum_{i=1}^{n}(MRi - MRpre,i) \,.\, \sum_{i=1}^{n}(MRi - MRexp,i)}{\sqrt{[\sum_{i=1}^{n}(MRi - MRpre,i)]} \,.\, \sqrt{[\sum_{i=1}^{n}(MRi - MRexp,i)]}} \text{ ------------------------------ (18)}$$

ii. Chi-square (x^2)

$$x^2 = \frac{\sum_{i=1}^{N}(MR_{exp.i} - MR_{pre.i})^2}{N-n} \quad \text{------------------------ (28)}$$

iii. Root mean square error (RMSE)

It's signifying the noise in the data (Demir *et al.*,2004; Doymaz,2005b; Wang *et al.*,2007):

$$RMSE = \left[\frac{\sum_{i=1}^{N}(MR_{pre.i} - MR_{exp.i})^2}{N}\right]^{1/2} \quad \text{---(20)}$$

iv. Mean bias error (MBE) (Kingsly *et al.*,2007)

$$MBE = \frac{\sum_{i=1}^{N}(MR_{pre.i} - MR_{exp.i})}{N} \quad \text{---(21)}$$

2.13 Study on quality of cocoa beans

Gro Cocoa (2004) reported that the tradition of excellence in cocoa Trinidad &Tobago extends into the realm of research.Pioneerung collaborative research on Cocoa fermentation and drying involving quality and flavor chemistry was undertaken at the Cocoa research unit (CRU) and Ministry of Agriculture,Land and Marine Resources (MALMR) in the 1960s & 1970s.This work formed the basis of subsequent studies on this subject in various research centers around the world. Investigations were re-initiated at CRU in 1995 to examine quality assessments in relation to fermentation and drying of selected Trinitario varieties.

CHAPTER THREE

3.0 Materials and Methods

3.1 Experimental Materials

Fresh cocoa pods (Amenlonado variety) were procured from a village called Oda, in Akure south local government Akure in Ondo State. Cocoa beans from damaged cocoa pods, dry or diseased beans, beans from black pods, germinated or germinating beans and small, unmatured beans were set aside and they are not used for the experiment but fresh ripe undamaged cocoa pods were selected from the whole lot.

3.2 The Solar dryer

A natural convection indirect solar dryer was used for the study. The solar dryer (Plate 6) has two main components: - drying chamber and solar collector. The dryer was design to maximize the use of energy available from the sun and reduce agricultural wastes.

Plate 6 Mobile Solar dryer

3.2.1 Solar collector

The solar collector is a flat plate type with dimension of 164cmx62cm. It has an air collection gap of 22.5cm and insulation of about 5cm thicknesses. The black painted aluminium screen sheet absorbing surface (absorbs transmitted heat energy through the glass glazing) is placed diagonally across the collector. A single tempered glass cover with a thickness of 5cm is placed above the absorber. The collector is attached to the back side of the drying chamber, oriented at an angle 8^0 to the horizontal. The convective current inside the chamber forces the ambient air to pass through the absorber (on the principle of matrix) and rise up to the load. It contains three major components as follows:

i. Glazing : -It is a transparent glass that allows solar radiation to pass through.
ii. Insulation :-It was insulated with straw board and plywood,thus reducing heat loss by conduction in the dryer.
iii. Aborsber :-it is the heart of the dryer ,it receives radiant energy concentrated on it by the glazing material and converts same to heat energy which heats the incoming air and pass across the drying chamber.

3.2.2 Drying Chamber.

The drying chamber is a cabinet type with a design capacity of 5kg of grains. The chamber accommodates a total of eleven (11) detachable trays which are old refrigerator trays with an interval of about 5cm to each other. They are placed in the chamber, with plastic gauze to ensure easy passage of heated air across the bed. The chamber was constructed using plywood, fibre glass and having its interior part lined with reflective surface. At the upper part of the chamber lies the outlet vents as seen in the plate. It ensures natural ventilation between the air intake and outlet of the warm air. It also has insulated roof inclined at an angle 30^0 .The drying chamber and trays is shown in Plate 7 below.

Plate 7 The Drying Chamber and the drying trays

3.3 Principles of Operation

The solar dryer uses convection currents to move solar heated air past the food to carry moisture away. The dryer consists of a glaze collector (tempered glass) and a drying chamber. Air vents at the top and bottom allow air to pass through and can be adjusted to allow for more or less air circulation in hotter or cooler climates, and to regulate the temperature inside the drying chamber. When the vents are open, the hot air rises after being preheated by the effect of solar radiation and escapes through the upper vents. While the cooler air at ambient temperature enters through the lower vents. The convection current set up then leaves the upper vents. All the vents were closed off with plastic gauze to prevent insects from entering.

The sun collector was set to face the southerly direction, with a tilt corresponding to the latitude of location of use (Akure), 8^0 so as to face the sun at midday and also allow rain water to drain off. Inside the collector, a piece of metal painted black absorbs energy from the sun and warms up. When this heat passes to the surrounding air, convection currents start. A sheet of Aluminium screens stores a lot of heat and ensures that the air keeps moving even when the sun goes behind the cloud. The absorber was secured in the middle of the collector to allow free air flows above, through and below.

Buoyant forces in the dryer induce the air flow due to differences in air density, which synchronize with pressure drops across the crop stacks. The working temperature of this project is the temperature at the upper vents minus the temperature at the lower vent of the dryer, which depends on the speed of the air current set up, the heat capacity of the air, and the rate of heat loss from the sides of the dryer.

The drying chamber comprised a timber frame and walls of plywood, with suspended drying trays inside suspended like drawers.

3.3.1 Tilt and Orientation of the Absorber

The quantity of solar energy intercepted in drying agricultural product is important. For the dryer to receive considerable energy needed for its operation, the surface always points to the sun to receive considerable radiant energy. However, the technology (mechanism) to track the sun is very expensive and not practicable for wide use. Therefore, a flat plate is always tilted and oriented in a way it receives maximum solar radiation during the desired season of use. Its inclination has the advantage of preventing dust and dust from clinging to the glass and reducing its transmittance.

The best stationary orientation is due south for location in the northern hemisphere and due north in the southern hemisphere. Therefore, for an optimum tilt angle, a south facing surface in the northern hemisphere will collect more energy per unit area than either a horizontal or vertical surface (Faber, 1961).

3.4 Breaking of Cocoa pods

Cocoa beans were used as test samples. The pods were broken with blunt object to prevent cutting or damaging the beans inside the pods and breaking of pods is done immediately.

3.5 Fermentation of Cocoa beans

The cocoa beans were fermented in a wooden box of 360cm by 180cm covered and lined with perforated plantain or banana leaves. The adhering sugary pulp becomes liquid and drains out of the box. The box is filled with the beans while the ends of the leaves that extend out of the basket are folded over to cover the beans and tightly held secured with logs or heavy stones. The mixing is done at the third day with temperature of 45°C and fifth day with temperature of 48°C, while the beans were fully fermented on the seventh day with temperature of 50°C. The main purpose of fermentation of cocoa beans is to develop the chocolate flavour and aroma, and to get rid of the pulp around the beans.

The correct fermentation and drying of Cocoa is of vital importance to the quality of cocoa products and no subsequent processing of the beans will correct for a bad practice. A good flavor in the final cocoa or chocolate is related closely to good fermentation but if drying after fermentation is retarded, mould develop and these impart very unpleasant flavor even if fermentation has been carried out correctly.

3.6 Drying Procedure

The solar drier was placed on latitude 8° from a meteorological station. The study begins on 25th of February, 2009 till 1st of April, 2009.This choice of location for the testing of the drying system was necessary because of the following reasons:

i. To subject all drying methods to the same environmental conditions.

ii. To install the systems in a location where reflected or re-radiated energy from surrounding buildings does not fall on the collector.

iii. To install the systems in a location where the collector will not be shaded at any time during the testing period.

iv. To make use of readily available instruments at the location.

Equal samples of wet fermented cocoa beans were spread evenly at a loading rate of $2.97g/cm^2$, $3.21g/cm^2$ and $3.97g/cm^2$ into the solar dryer and in the open sun drier for the dehydration test as shown in Plate 8and 9 . The experiment was replicated thrice and the mean value was used. The following data were recorded during the experimental tests.

a. The incident solar radiation intensity using a tube net Radiometer.
b. The global solar radiation intensity using a global radiometer.
c. The weight of cocoa beans being dried using digital weighing meter with a precision of 0.1g and the moisture contents were estimated using the equation 15.

d. The absorber temperature and dryer's temperature using a digital probe thermometer.

e. The relative humidity and ambient temperature using the humidity-temperature meter

Plate 8 Drying with indirect Solar dryer

Plate 9 Drying in the Open Sun

3.7 Physical Quality Assessment

Quality, in all its forms, is an essential building block for a sustainable cocoa economy to secure the future of the industry. It is hard to reconcile the concept of cocoa as a high quality food ingredient when one sees evidence of poor quality practices such as the degradation of cocoa beans with debris, poor drying which results in mould, slates from unfermented cocoa beans and inappropriate storage. All the samples of cocoa beans were examined for colour, occurrence of slate or mould and pH. The cut test is used to examine the physical quality assessment of the beans. The cut test is performed on raw cocoa beans which has been fermented and dried to determine the grading acceptability. It is used for the assessment of the degree of fermentation, uniformity and the number of defective beans, broken beans as well as those damaged by insects and rodents.

3.7.1 The Cut Test

This was carried out according to Malaysian standard MS 293.

i. Samples for inspection and analysis were taken at random from the beans.

ii. The samples were thoroughly mixed and 300 beans were counted off, irrespective of size, shape and condition.

iii. The weight of the 300 beans was obtained by weighing on a scale.

iv. The 300beans were cut lengthwise through the middle and examined. Separate counts of the number of beans with defects, mouldy, slaty, insect damaged, germinate or flat were counted.

Where a bean was defective in more than one respect, only one is counted and the defect to be counted will be the defect, which occurs first in the foregoing list of defects. The examination is normally carried out in good daylight or equivalent artificial light and the results of each kind of defects were expressed as a percentage of the 300 beans examined.

$$\text{Percentage defect} = \frac{\text{number of defective beans}}{300} * 100 \quad (22)$$

Table 4 Grade standard of cocoa beans

Defects	Grade One	Grade Two	Sub standard
Mould	Maximum of 3%	Maximum of 4%	If fails to reach grade two standard
Slatey	Maximum of 3%	Maximum of 8%	
Other	Maximum of 3%	Maximum of 6%	

Source :(Anon., (1995)

3.7.2 Identification of defects in Cocoa beans

Defects normally affect the quality of the final or end product of cocoa bean. Thus defects occur in many forms and affect the final product in different ways .This includes

a. Mould: it shows a visible mould internally which result from the wetness and it affects the acid and free fatty values. The higher the proportion of mould the higher the moisture content and free fatty acid which is undesirable in cocoa butter.
b. Slatey: A bean with a dark grey colour that gives a bitter taste and flavor. It is caused by unfully fermentation of cocoa beans before it s dried.
c. Germination: It is a missing radical in the cocoa beans and through the hole created the beans is infected.
d. Flat beans: A cocoa bean of which the cotyledons are too thin to cut.
e. Insect damaged: Visible larvae of insect and shows signs of damage, which are visible to the naked eye.

3.8 Chemical Assessment

The chemical assessment of the quality of the cocoa bean was based on the pH. Thé pH were determined according to Duncan *et al.,* (1989).Ten grammes of the nibs were homogenized in 200ml boiled distilled water, the homogenate was filtered with filter paper and cooled to 20-25°c.pH was determined using a pH meter (CD 70,MPA).

3.9 Data Analysis

The data obtained from the physical and chemical analyses were analyzed by using one way ANOVA and Bonferron multiple range tests with 5% significant level

3.10 Moisture content determination

The moisture content of the fermented cocoa beans was determined using the vacuum oven method at 70^0C for 24hours (AOAC, 1990).This experiment was done in two replicates. The average of the two replicates were taken and used as the initial moisture content of cocoa beans. This method was used for the three loadings and the moisture content was expressed as

$$\text{Moisture content wet basis } (MC_{wb}) = \frac{\text{Weight of water in the product}}{\text{Weight of wet product}} \times 100$$

$$MCwb(\%) = \frac{Ww}{Ww + Wd} * 100 \text{--- (23)}$$

Initial moisture content, M_i

$$M_i = \frac{w_i - w_d}{w_d} \text{-- (24)}$$

Where W_i is the initial weight of sample and W_d is the weight of the dry solid.

Moisture content at any time , M_t

$$M_t = \frac{(m_i + 1) * w_t}{w_i} - 1 \text{-- (25)}$$

Where W_t is the weight of sample at any time, t.

The moisture at any time was calculated according to equation (25).

3.11 Mathematical modeling of drying curves

Thin layer drying refers to the drying of grains fully exposed to the ventilating air causing all grains to dry uniformly throughout the drying layer. Thin-layer drying is the process of removal of water from a porous media by evaporation, in which excess drying air is passed through a thin layer of the material until the equilibrium moisture content (EMC) is reached. Moisture removal from an agricultural product depends on their drying temperature, velocity and relative air humidity, variety and maturity (Yadollahinia *et al.*, 2008).

Thin-layer drying models describe the drying behaviour of biological materials. They fall into three categories, namely, theoretical, semi-theoretical, and empirical. The semi-theoretical models are generally derived by simplifying general series solutions of Fick's second law or modification of simplified models and valid within the temperature, humidity, airflow rate and moisture content range for which they were developed (Ozdemir and Devres, 1999). They are simplified and added with empirical coefficients in some cases to improve curve fitting. In the empirical models a direct relationship is derived between moisture content and drying time. Many researchers have worked on many thin layer models in the past and this study will consider thirteen (13) of them. Table 3.1 shows the thirteen (13) thin-layer models; the authors and their equations. The moisture ratio, MR is given as follows:

$$MR = \frac{M - Me}{M - Me} \qquad \text{(26)}$$

Where MR is the dimensionless moisture ratio or unaccomplished moisture content

M is the moisture content at any time during drying, Me is the equilibrium moisture content M_o is the initial moisture content inkg[H_2O]/ kg[DM], respectively.

Table 5 Thin layer models by different researchers used for drying curve of cocoa beans.

Model name	Model equation	References
Newton	$MR = \exp(-kt)$	Ayensu,(1997);Togrul & Pehlivan,(2004); Upadhyay et al.,(2008);Mujumdar,(1987).
Page	$MR = exp(-kt^{n})$	Kaleemullah Kaleemullah & Kailappan,(2006);Saeed et al.,(2006);Senadeera et al.,(2003); Diamante and Munro (1993).
Modified page	$MR = \exp\left[-(kt)^{n}\right]$	Goyal et al.,(2007);Ceylan et al.,(2007);Sogi et al.,(2003); White,Bridges,Loewer & Ross (1978).
Henderson and Pabis	$MR = a exp(-kt)$	Kashaninejad et al.,(2007);Saeed et al.,(2006);Ozdemir & Devres,(1999); Zhang and Litchfield (1991).
Logarithmic	$MR = a exp(-kt) + c$	Babalis et al.,(2006);Celma et al.,(2007);Lahsasni et al., (2004);Yagcioglu,Degirmencioglu,and Cagatay (1999).
Two-term	$MR = a exp(-k_{0}t)\, b exp(-k_{1}t)$	Lahsasni et al., (2004);Rahman et al.,(1998);Wang et al.,(2007)., Henderson (1974).
Two-term exponential	$MR = a exp(-kt) + (1-a)\exp(-kat)$	Midilli & Kucuk, (2003);Sacilik et al.,(2006);Tarigan et al., (2007); Sharaf-Eldeen,Blaisdell,and Hamdy(1980).
Wang and Singh	$MR = 1 + at + bt^{2}$	Wang and Singh (1978).
Approximation of diffusion	$MR = a exp(-kt) + (1-a)\exp(-kbt)$	Wang et al., (2007);Yaldiz and Ertekin (2001);Togrul & Pehlivan (2002).
Modified Henderson and Pabis	$MR = a exp(-kt) + b exp(-gt) + c exp(-ht)$	Karathanos (1999).
Verma et al	$MR = a exp(-kt) + (1-a)\exp(-gt)$	Doymaz,(2005);Karathanos, (1999);Yaldiz &Ertekin,(2001); Verma,Bucklin,Endan,and Wratten (1985).
Midilli and Kucuk	$MR = a exp(-kt^{n}) + bt$	Midilli and Yapar (2002).
Thompson	$t = a\ln MR + b(ln(MR))^{2}$	Thompson,Peart and Foster (1968).

Where k, k_0, k_1 are drying rate constants while a, b, c, g are constants.

3.12 Statistical Analysis of Thin-Layer Models.

Modeling drying behaviour of different agricultural products often requires the statistical methods of regression and correlation analysis. The goodness of fit of the tested models to the experimental data are the coefficients of determination, R^2, the reduced chi-square χ^2,mean bias error and root mean square error (RMSE) for the tested models. R^2 was the primary criterion to select the best model to account for the variation in the drying data obtained by Sacilik and Unal, (2005) and Yadollahinia *et al.*, (2008). For quality fit, R^2, value should be higher and χ^2, MBE and RMSE values should be lower (Togrul and pehlivan, 2002; Erenturk *et al.*, 2004;Kingsly *et al.* 2007).Yadollahinia *et al.* (2008) performed his non-linear regression analysis by SPSS 10.5(Statistical Package for Social Science) software while Akpinar and Bicer (2008); Usavadee and Marina (2009) used STATISTICA computer programme to perform their regression analysis. Sigma plot and Excel Statistical software were used in this study.

a. Coefficient of determination (R^2)

$$R^2 = \frac{\sum_{i=1}^{n}(MRi - MRpre.i) \; . \; \sum_{i=1}^{n}(MRi - MRexp.i)}{\sqrt{[\sum_{i=1}^{n}(MRi - MRpre.i)]} . \sqrt{[\sum_{i=1}^{n}(MRi - MRexp.i)]}} \quad \text{------------------------------} \; (27)$$

b. Chi-square (x^2)

$$x^2 = \frac{\sum_{i=1}^{N}(MR_{exp.i} - MR_{pre.i})^2}{N-n} \quad \text{------------------------------} \; (28)$$

c.Root mean square error (RMSE)

$$RMSE = \left[\frac{\sum_{i=1}^{N}(MR_{pre.i} - MR_{exp.i})^2}{N}\right]^{1/2} \quad \text{------------------------------} (29)$$

d.Mean bias error (MBE)

$$MBE = \frac{\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})}{N} \quad \text{--(30)}$$

Where $MR_{exp,i}$ is ith experimentally observed moisture ratio, $MR_{pre,i}$ is ith predicted moisture ratio, N is the number of observation, n is the number of constants.

CHAPTER FOUR

4.0 Results and Discussion

4.1 Physical and Chemical Quality.

The results obtained from the cut test shows that all the sample were properly dried having dark reddish colour, with low number of mould, slatey and germinated beans as shown in Figure 4 below

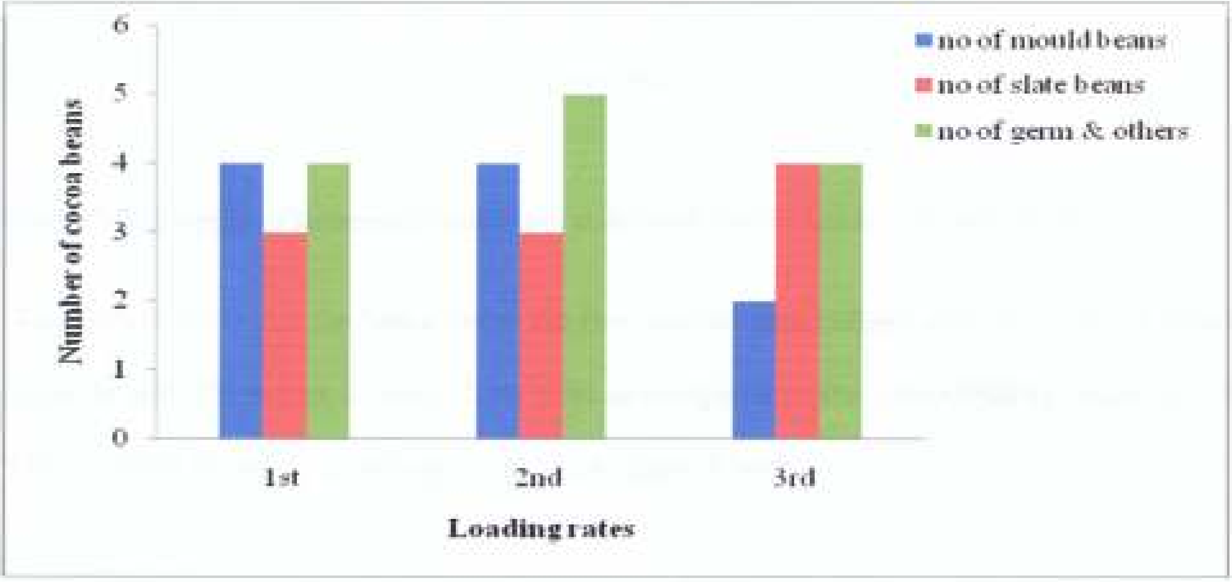


Figure 4. The cut test of fermented cocoa beans in the three loading rates.

In all the test attributes, the solar dried samples compared favourably with the sun-dried samples. The qualities of both solar dried and sun dried sample are within the acceptable level in international standards and they all fall in grade one standard with the third loading rate showing light crop due to its weight as shown in Figure 4.

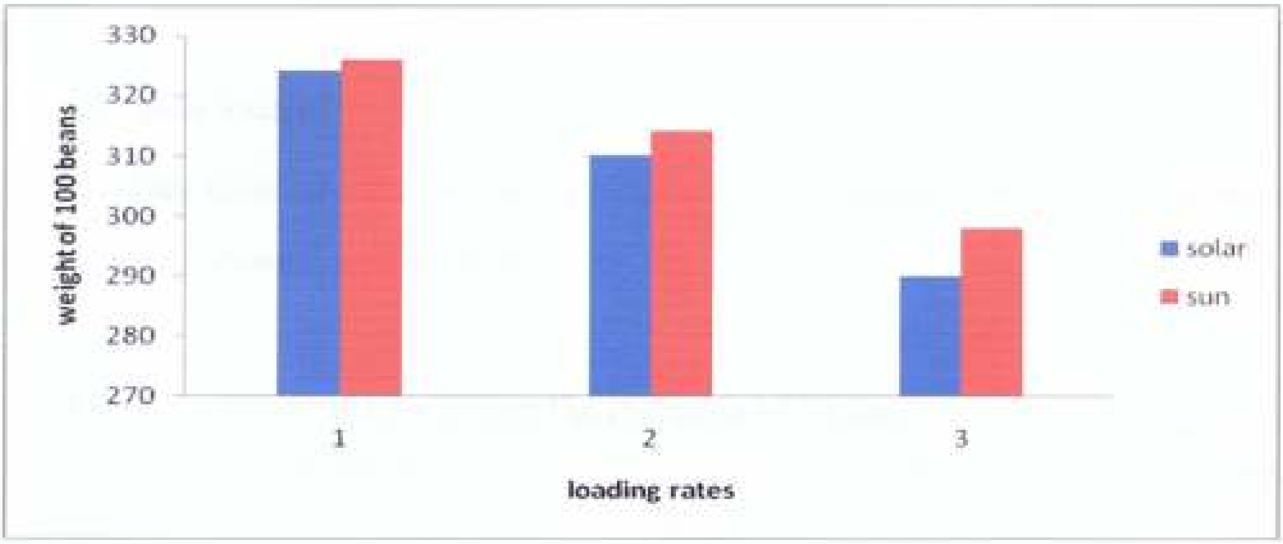


Figure 5. The weight of fermented cocoa beans at different loading rate in solar and sun drying.

Test results show that the beans under the free convectional indirect solar dryer are of superior qualities with pH values between 5.50- 6.00 as compared to the corresponding values of 4.50-5.00 recorded for open sun drying as shown in Figure 6 below.

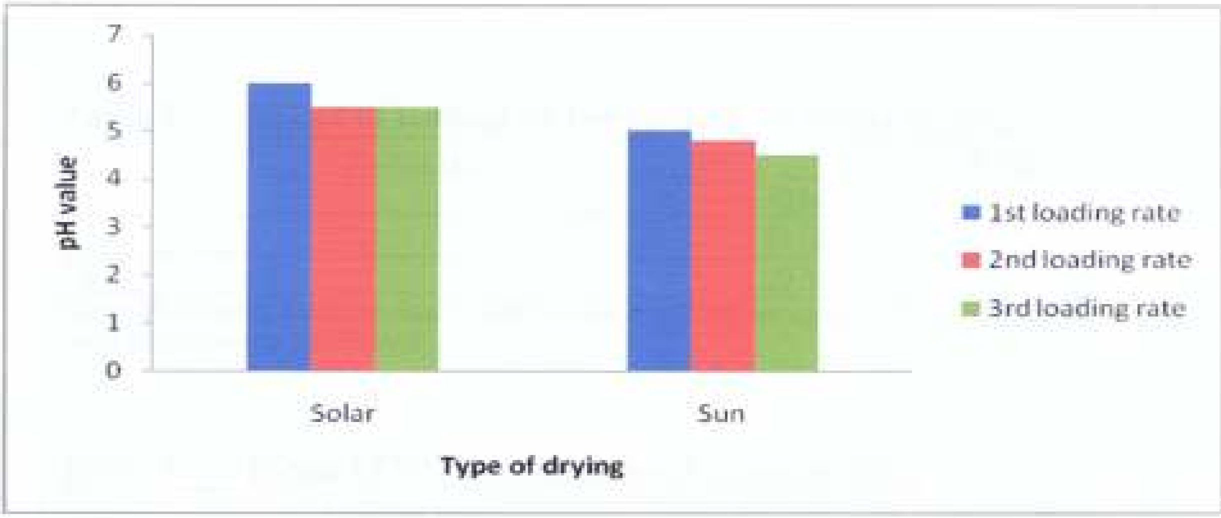


Figure 6. The pH value of fermented cocoa beans in solar drying and sun drying

4.2 Data Analysis

The Data Collected were analyzed by using analysis of variance (ANOVA) and the result obtained is shown in the table below,

Table 6 Effect of Loading on the Duration of Drying

Loading (g)	Duration of Drying (hr)
3.97	33.5b
3.21	26.5a
2.97	21a

Mean values having a common letter within the same column are not significantly different according to Bonferroni multiple range test at the 5% level.

Table 7 Effect of the drying methods on the duration of Drying

Drying Method	Duration of Drying (hr)
Solar Drier	24a
Sun Drying	30b

Mean values having a common letter within the same column are not significantly different according to Bonferroni multiple range test at the 5% level.

Table 8 Effect of loading on the quantity of beans in 300g

Loading (g)	Weight (g)
3.97	325a
3.21	317a
2.97	291a

Mean values having a common letter within the same column are not significantly different according to Bonferroni multiple range test at the 5% level.

Table 9 Effect of loading on the no of beans in 100g

Loading (g)	No of Beans
3.97	84.5a
3.21	99a,b
2.97	108b

Mean values having a common letter within the same column are not significantly different according to Bonferroni multiple range test at the 5% level

4.3 Temperature and Solar Irradiance

The 3.97g/cm^2 of fermented cocoa beans at an initial moisture content of 56.06% wet basis was dried for testing the solar dryer performance compared to open sun drying. Experiments were continuously carried out for an average of 5 hours. During drying time periods, the solar radiation on the absorber surface (*IT*) and temperatures of solar drying (*Td*) and ambient air (*Ta*) were recorded at 60 min intervals and presented in Figure 7. The maximum temperature 40^{o}C.The average temperature difference of air inside the dryer and ambient air was about 2-3°C.

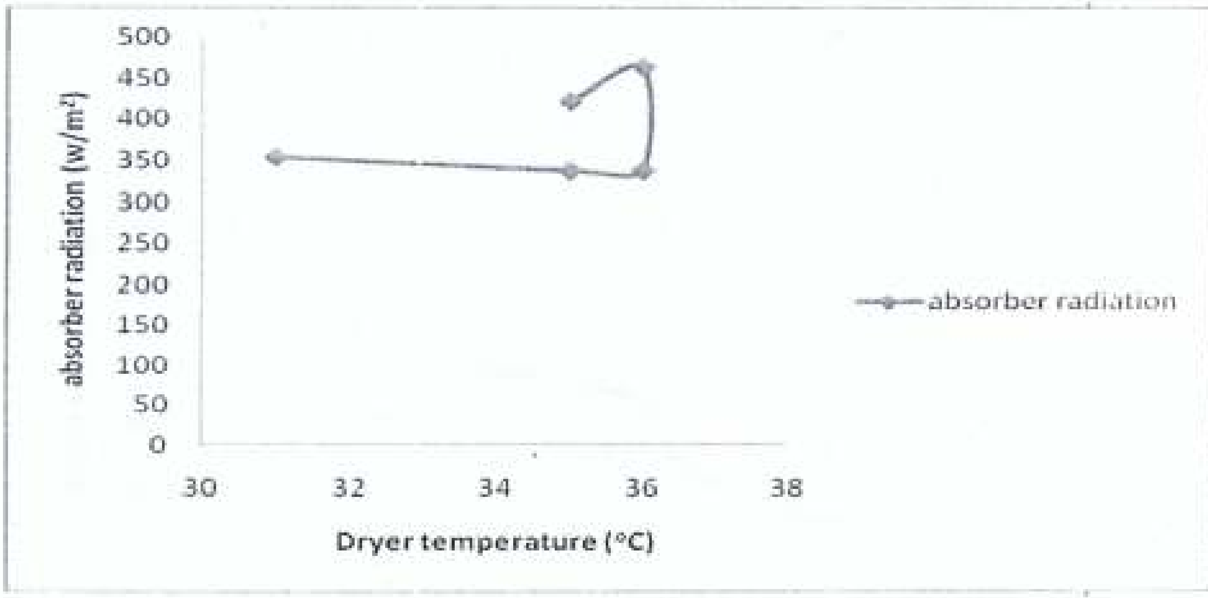


Figure 7. Variation in the absorber radiation and the solar dryer temperature

4.4 Drying Kinetics of Fermented cocoa beans

From the experimental data, the moisture content (%wb) of fermented cocoa beans for the solar dryer and open sun drying at any time are represented in Figure 8- 10. It was clearly evident from these curves that the drying rate of fermented cocoa beans in the solar dryer was faster than that of the open sun drying. The moisture content of the fermented cocoa beans reached 6.5%wet basis in 32hours of drying in the solar dryer, whereas the final moisture of the same product dried by open sun drying was only 9.87% wet basis thus moisture content was not enough for safe storage. When it was dried under open sun drying, the duration of drying was about two (2) sunshine days to bring it to the same moisture level.

This can be explained that the main factor influencing drying rate was the drying air temperature. Compared to open sun drying, solar dryer can generate higher air temperature and affected the significant increasing of evaporation rate of water and then result in lower final moisture content of drying samples. These results indicated that solar dryer was effective than open sun drying.

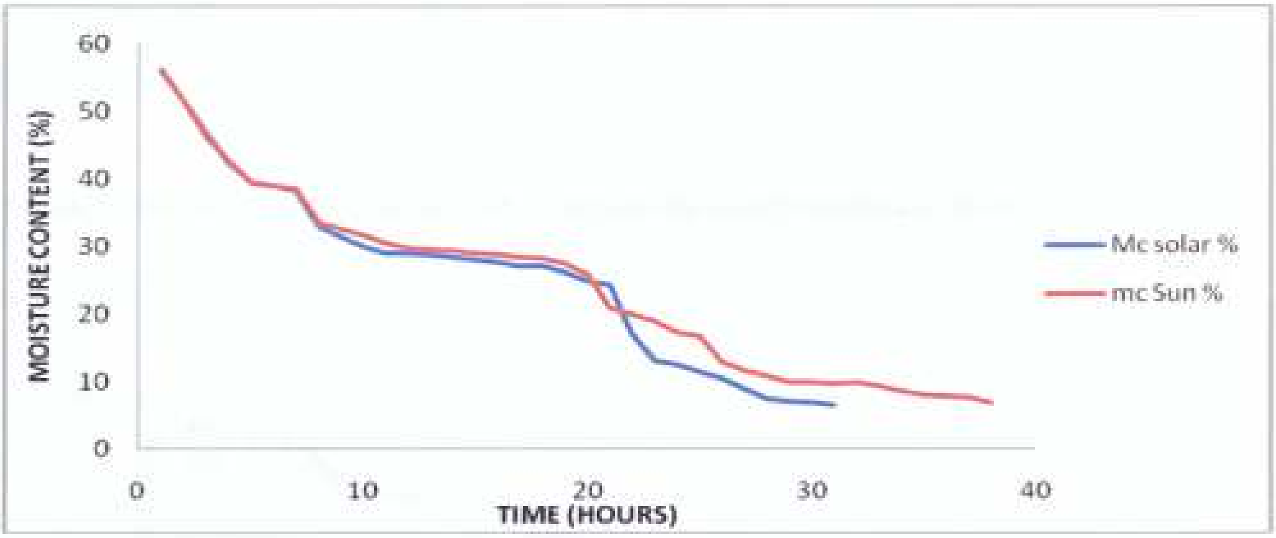


Figure 8. Variation of moisture content with drying time for fermented cocoa beans for 3.97g/cm^2

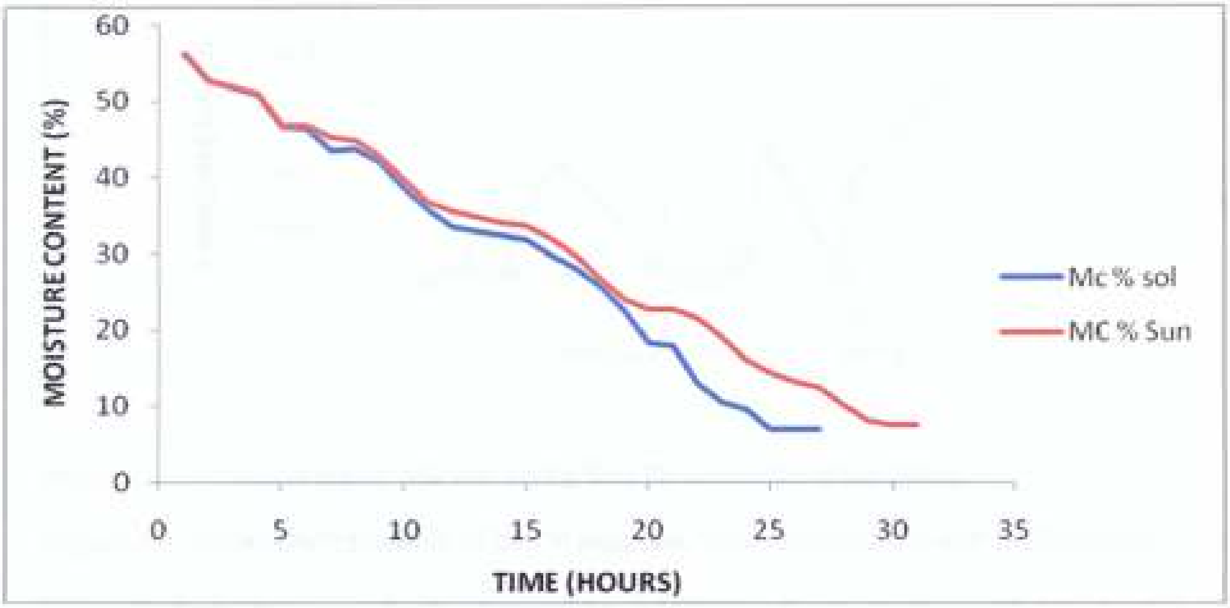


Figure 9. Variation of moisture content with drying time for fermented cocoa beans for 3.21g/cm²

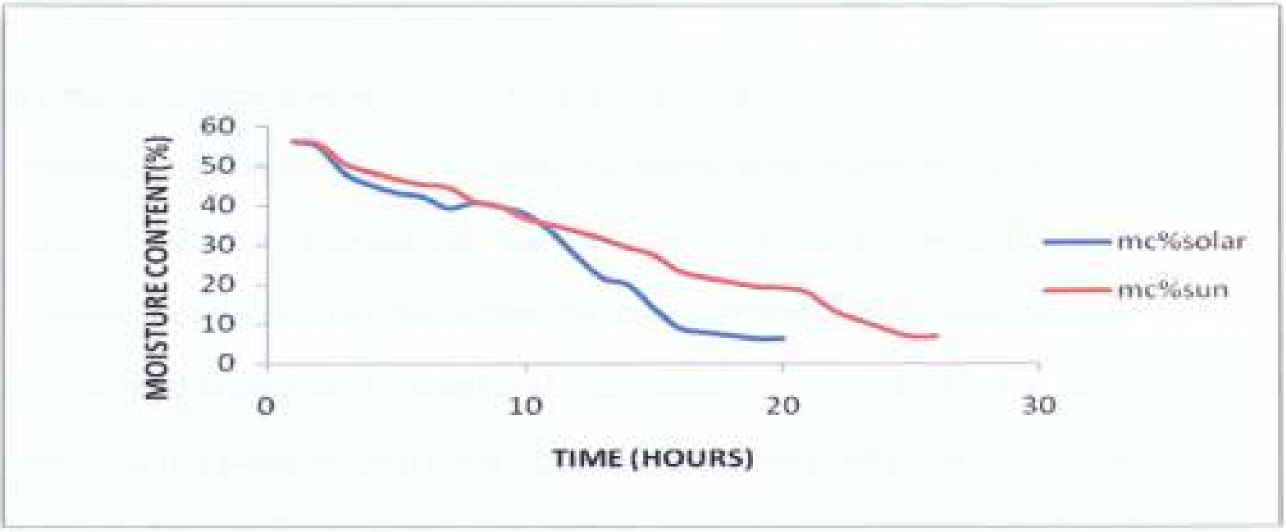


Figure 10. Variation of moisture content with drying time for fermented cocoa beans for 2.97g/cm²

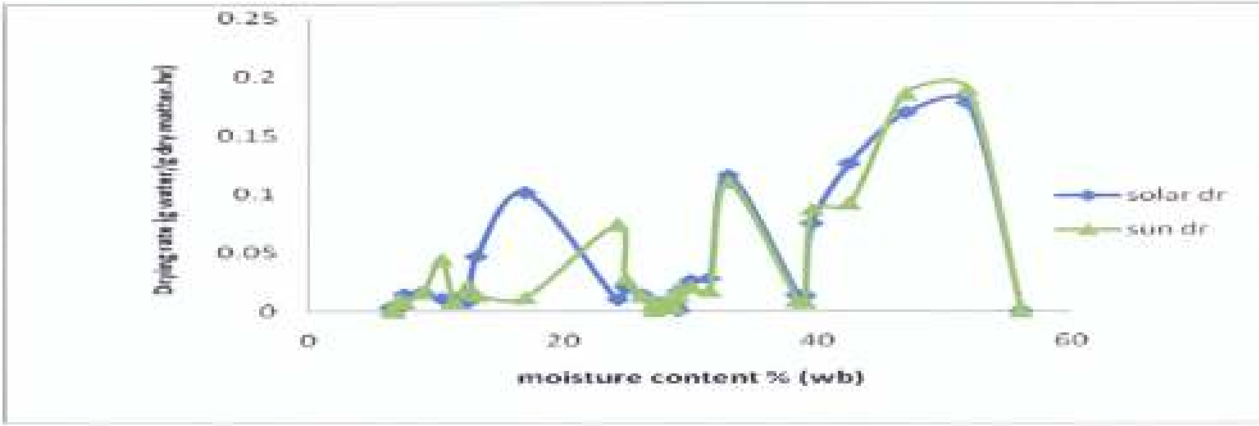


Figure 11. Variation of drying rate with drying time for fermented cocoa beans.

Figure 11. shows the variation of the drying rate with moisture content of fermented cocoa beans for both drying methods, obtained by calculating from experimental data. Drying rate decreased continuously with decreasing moisture content or increasing drying time. Similar results have been reported by Mohammed *et al*. (2009) for kiwifruit, Bala *et al*.(2003)for pineapple Prachayawarakorn *et al*.(2008) for banana and for different crops by researchers (Kingsly and Singh,2006;Doymaz,*et al*.,2005).

Furthermore, there is no any constant rate drying period in these curves, and all the drying operations are seen to occur in the falling rate period, In the falling rate period, the material surface is no longer saturated with water, and the drying rate is controlled by diffusion of moisture from the interior of the solid to the surface (Doymaz 2007;), which is dependent on the moisture content of the samples (Prachayawarakorn *et al*., 2008). The same drying behaviour is reported for long green pepper(Akpinar &Bicer ,2008).The drying rate for the open sun drying decreases continuously with decrease in moisture content and is much lower as compared to that for solar dryer so the amount of moisture removed in open sun drying is relatively smaller.

Table 4.5 Modeling of moisture ratio to drying time for thin layer convection solar dryer of fermented cocoa beans.

MODELS	COEFFICIENT			R^2	x^2	MBE	RMSE	R. sum	Av. Rank
Newton	k=0.0186			0.9311(12)	0.0134(8)	0.0666(9)	0.0130(8)	37	9.25
	k=0.0383	n=0.8255		0.9351(10)	0.0108(6)	0.0546(7)	0.0105(6)	29	7.25
Modified Page	k=0.0192	n=0.8255		0.9351(10)	0.0675(9)	0.2350(10)	0.0654(9)	38	9.5
Henderson &Pabis	k=0.0160	a=0.8748		0.9506(6)	0.0085(2)	0.0421(6)	0.0082(3)	17	4.25
Logarithmic	k=0.0057	a=1.5578	c=-0.7343	0.9662(2)	0.0088(4)	0.0411(5)	0.0082(3)	14	3.5
Two Term	ko=0.0162	k1=0.0160	a=0.4523	0.9506(6)	0.0087(3)	0.0407(3)	0.0081(2)	14	3.5
	b=0.4226								
Two Term Mod.	k=0.2539	a=0.0684		0.9398(9)	0.0114(7)	0.0588(8)	0.0107(7)	31	7.75
Wang &Singh	a=-0.0139	b=5.0149		0.9234(13)	1.1000(13)	20672(13)	106465(13)	52	13
Appro Of Dif	k=1.1408	a=0.1712	b=0.0133	0.9562(4)	0.2088(10)	0.0379(1)	0.2021(10)	25	6.25
Mod Hender &Pab	k=0.0165	a=0.2746	b=0.2954	0.9506(6)	0.0090(5)	0.0410(4)	0.0082(3)	18	4.5
	c=0.3049	g=0.0160	h=0.0158						
Verma Et Al	**k=1.1444**	**a=0.1705**	**g=0.0152**	**0.9562(4)**	**0.0069(1)**	**0.0383(2)**	**0.0067(1)**	**8**	**2**
Midilli & Kucuk	k=0.2021	n=0.1734	a=1.0050	0.9787(1)	0.4659(11)	0.5296(12)	0.4358(11)	35	8.75
	b=0.0049								
Thompson	a=-64.7773	b=-8.0810		0.9655(3)	0.8923(12)	0.8673(13)	0.9568(12)	40	10

Table 4.6 Modeling of moisture ratio to drying time for thin layer open sun drying of fermented cocoa beans

MODELS	COEFFICIENT			R^2	χ^2	MBE	RMSE	R. Sum	Av. Rank
NEWTON	k=0.0199			0.9423(12)	0.0089 (9)	0.0261(9)	0.0086(9)	39	9.75
PAGE	k=0.0710			0.9617(9)	0.0063(7)	0.0167(7)	0.0061(7)	30	7.5
MODIFIED PAGE	k=0.0217	n=0.6905		0.9617(9)	0.1376(11)	0.3456(11)	0.1339(11)	42	10.5
HENDERSON &PABIS	k=0.0160	a=0.8334		0.9741(6)	0.0044(4)	0.0075(4)	0.0042(4)	18	4.5
LOGARITHMIC	k=0.0125	a=0.9083	c=-0.0955	0.9770(5)	0.0038(3)	0.0039(1)	0.0037(3)	12	3
TWO TERM	ko =0.0160	k1=0.0161	a=0.4507	0.9741(6)	0.0045(5)	0.0069(2)	0.0042(4)	17	4.25
	b=0.3827								
TWO TERM MOD.	k=0.1656	a=0.1071		0.9572(11)	0.0070(8)	0.0224(8)	0.0066(8)	35	8.75
WANG &SINGH	a=-0.0144	b=5.3256		0.9149(13)	1.2700(13)	1.0671(13)	1.1197(12)	51	12.75
APPRO OF DIF	k=0.8487	a=0.2269	b=0.0173	0.9827(2)	0.0032(2)	0.0090(6)	0.0031(2)	12	3
MOD HENDER &PAB	k=0.0159	a=0.2610	b=0.2814	0.9741(6)	0.0048(6)	0.0070(3)	0.0042(4)	19	4.75
	c=0.2909	g=0.0161	h=0.0161						
VERMA ET AL	k=0.8584	a=0.0226	g=0.0147	0.9827(2)	0.0135(10)	0.0934(10)	0.0132(10)	32	8
MIDILLI & KUCUK	**k=0.1921**	**n=0.3235**	**a=1.0040**	**0.9866(1)**	**0.0024(1)**	**0.0078(5)**	**0.0023(1)**	**8**	**2**
	b=-0.0023								
THOMPSON	a=-59.2342	b=-4.0169		0.9827(2)	0.3246(12)	0.8456(12)	1.4672(13)	39	9.75

Av.Rank- Average rank ,   R.sum-rank sum

4.5 Mathematical Modeling

The moisture content data at different experimental modes were converted to the more useful moisture ratio expression, and curve fitting computations with drying time were performed with the thirteen (13) drying models presented by previous workers (Table 5).The results of the statistical analyses undertaken on these models for the natural convention solar drying and the natural sun drying are given in Table 10 and 11,respectively.The models were evaluated based on Coefficient of determination (R^2), Chi-square (x^2), Mean Bias Error (MBE) And Root Mean Square Error (RMSE).The acceptability of the drying model was based on a value for the correlation coefficient R ,which should be closer to1,and low values for chi-squared, mean bias error and root mean squared error. All equations gave consistently high (R) values in the range of 0.9149 -0.9866.This indicates that all equations could satisfactorily describe the solar drying rates of fermented cocoa beans.

The result of RMSE ranges from 0.0067-106465, chi-square ranges from 0.0069-1.1000 and MBE values ranges from 0.03791-20672 for solar drying while RMSE ranges from 0.0023-1.4672, chi-square ranges from 0.0024-1.2700 and MBE values ranges from 0.0039-1.0671.

The result shows that for all thin layer drying models for all drying conditions of solar drying ,the Verma *et al.* (1985) model gave the best fit with R^2 =0.9562 , x^2=0.0069 ,MBE= 0.0383, and RMSE=0.0067 for solar drying .The Midilli model gave the best fit with R^2 =0.9866, x^2=0.0024, MBE =0.0078and RMSE=0.0023 for open sun drying. The drying constants (k) and (b) and coefficients (a) and (n) values and also the statistical parameters R^2, x^2,MBE and RMSE are shown in Table10 and 11 for both solar drying and open sun drying.

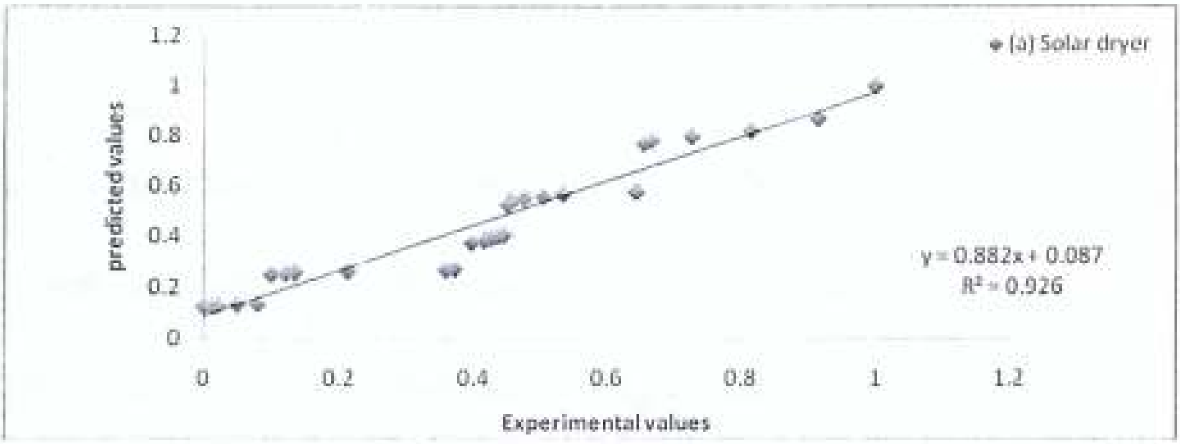


Figure 15 Comparison of experimental and predicted dimensionless moisture ratio by the resulting model solar drying

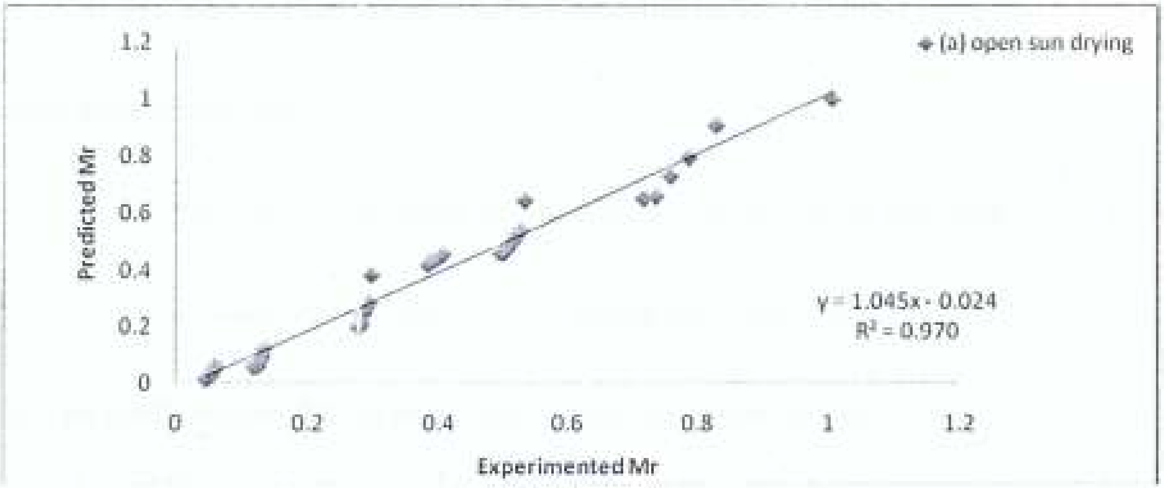


Figure 16 Comparison of experimental and predicted dimensionless moisture ratio by the resulting model for open sun drying

Validation of the Vermal *et al* and Midilli and Kucuk models was made by comparing the predicted moisture ratio with the experimented moisture ratio values from all the tests. The performance of the Vermal *et al* model for the thin solar drying and the Midilli and Kucuk model for natural sun drying was illustrated in Figures 15 and 16.The predicted data is banded around the straight line which showed the suitability of the Vermal *et al* and Midilli and Kucuk model in describing the drying behaviour of fermented cocoa beans in solar and open drying respectively.

CHAPTER FIVE

5.1 Conclusions

It can be concluded from the experimental result that convective indirect solar dryer was found to be simple, compact and more effective for fermented cocoa beans drying than open sun drying. It can dehydrate 3.97g/cm^2 of fermented cocoa beans in 32 hours in solar dryer and open sun drying took 38 hours this resulted in saving to the extent of 17% of drying time. Constant drying rate period was not observed under any test conditions of this investigation, the fermented cocoa beans drying occurring in the falling rate.

The result from the cut test showed that all the dried cocoa beans falls in the first grade cocoa standard on the international standard which indicates good quality cocoa beans for both solar dryer and sun drying. Test results showed that the beans dried in free convectional indirect solar dryer were of superior qualities with pH values between 5.50- 6.00 against the corresponding values of 4.50-5.00 obtained under open sun drying. The cocoa beans which are of good quality attract high market price where those of lower or bad quality (due to debris, poor drying and inappropriate storage) are subjected to a discount. solar dryer turned out a higher quality product than the open/traditional sun drying method as the latter is subjected to excessive contamination, dirt and insect infection. These defects were naturally eliminated by the construction and operating condition of solar dryer as the products were not directly exposed to the air. The solar dryer proves useful for local farmer as it ensures high quality, good colour and flavor and reduces the drying time. It does not pollute the environment and requires minimal maintenance once it is installed.

In order to explain the drying behaviour and the mathematical models of fermented cocoa beans, thirteen models were applied to thin layer convective indirect solar dryer and open drying processes. The result showed that the Verma *et al* model was found to be the most suitable model for describing the drying curve of the convective indirect solar drying process of cocoa beans with R^2=0.9562 ,x^2=0.0068, MBE=0.0383 and RMSE=0.0067 while, the Midilli and Kucuk model, best described satisfactorily the drying curve of fermented cocoa beans under open sun with R^2 = 0.9866,x^2=0.0024,MBE=0.0078 and RMSE=0.0023.

5.2 Recommendations

From the observation made during the study the following are recommended for consideration.

a. The indirect solar drier is recommended for use by farmers. This is based on the fact that it is a cheaper alternative in terms of cost and convenience.

b. The performance of the dryer with draught ventilation conditions to make better use of the heated air should be investigated.

c. The use of colour meters in assessing the quality of dried cocoa beans should be considered.

REFERENCES

Abe, T., Hikida, Y., Ofoche, C.E. and Yamashota, J. (1992) Effects of drying parameters on quality of artificially dried rough rice. Journal of Agricultural Mechanization in Africa,Asia and Latin America, 23 : 42-46.

Abiola S.S. and Tewe O.O. (1986), Effects of cocoa husk on the performance of cockerels. Journal of Agriculture Science and Technology, 2(2): 131-134.

Ahankorah, V., Appiah, M.R., Halm, B.J. and Dodoo, R.E. (1987) Production and utilization of cocoa pod husk as a source of people fertilizer. Proceeding of 10th International Cocoa Research Conference, Sonato Domingo, Dominican Republic. May 17-23: 843-848.

Akinsoyinu, A.O and Adeloye, A.A. (1987) Studies on the utilization of cocoa (Theobroma cacao L.) seed shells by sheep and goats in Nigeria. Proceeding of 10th International Cocoa Research Conference, Sonato Domingo, Dominican Republic. May 17-23: 867-871.

Allision, H.W.S. and Kenten, R.H. (1959) Tray fermentation of West African Amelindo cocoa. First FAO Technical Cocoa meeting, Accra, Ghana. February 8-15 paper of the 6th technical session.

Allision, H.W.S. and Rohan, T.A. (1958) A new approach to the fermentation of West African Amelindo cocoa. Journal of Tropical Agriculture 35: 279-288

Are, L.A. and Gwyme-Jones, D.R.G. (1974) Cocoa in West Africa. Oxford University press Ibadan.

Ayensu, A. (1997) Dehydration of food crops using a solar dryer with convective heat flow. Solar Energy, 59:121-126

Akpinar E.K. (2006a) Mathematical modeling of thin layer drying process under open sun of some aromatic plants. Journal of Food Engineering 77 (4): 864-870.

Akpinar E.K. (2006b) Determination of suitable thin layer drying curve model for some vegetables. Journal of Food Engineering 73 (1): 75-84.

Akpinar E. K. and Bicer Y. (2008) Mathematical modeling of thin layer drying process of long green pepper in solar dryer and under open sun. Energy Conversion and Management, 49: 1367-1375.

Anon (1995) Specification for grading of Malaysian cocoa beans (3rd revision) SIRIM, Malaysia.

AOAC (1990) Official Methods of Analysis (15th edition) Association of Official Analytical Chemists, Washington DC

Ayensu,A.(1997) Dehydration of food crops using a solar dryer with convective heat flow. Solar Energy 59:121-126

Babalis, S. J., Papanicolaou, E., Kyriakis, N., and Belessiotis, V. G. (2006). Evaluation of thin-layer drying models for describing drying kinetics of figs (Ficus carica).Journal of Food Engineering 75(2) :205-214.

Bala, B.K., Mondol, M.R.A., Biswas, B.K., Chowdury B.L. and Janjai, S. (2003) Das Solar drying of pineapple using solar tunnel drier. Renewable Energy, 28:183-190.

Bala, B.K. and Wood, J.I. (1994) Simulation of indirect natural convention solar drying of rough rice. Journal of solar energy 53:259-266.

Bansal, N.K., Mantred, K., and Michael, M. (1990) "Renewable Energy sources and Conversion Technology" Tata McGraw-Hill Publishing.

Barre, H.J, Baughman, G.R. and Handy, M.Y. (1971) Application of the logarithmic model to cross-flow deep-bed grain drying. Transactions of the American Society Agricultural Engineering, 14(6) pp 1061-1064

Baryeh, E. (1985) Cocoa drying and storage using charcoal and solar heated rodes. Journal of Agricultural Mechanization in Africa,Asia and Latin America. 16(1): 23-28

Bjorge, M. (1998). A review of solar food drying. Retrieved from Url:http://www.alivefoods.com/dehyd.html

Carneige, E.J. and Pohl, J.G. (1980) "Food Dehydration Solar Energy handbook". Edited by Dickinson, W.C and Heremisinoff, P.N. Mariel Dekker Inc.

Celma, A. R., Rojas, S., Lopez, F., Montero, I., and Miranda, T. (2007) Thin-layer drying behavior of sludge of olive oil extraction. Journal of Food Engineering 80:1261-1271.

Ceylan, I., Aktas, M. and Dogan, H. (2007) Mathematical modeling of drying characteristics of tropical fruits.Applied Thermal Engineering 27:1931-1936.

Clark, W.A. (1980). Plans for an Appalachian Solar Food Dryer. ASPI Publications, Mount Vernon, Kentuky.

Chocolate Manufacturers Association (2003) The Cocoa tree from bean to bar. http;//www.Cocoa tree organization from bean to bar.

Diamente, L.M. and Munro, P.A. (1993) Mathematical modeling of the thin layer solar drying of sweet potato slices, Solar Energy 51(4):271-276.

Dincer, I. (1996) Sun drying of Sultane grapes. Drying Technology, 14:1827-1838.

Donald,Mc.,Lass,R.A and Lopez,A.S.F. (1981) Cocoa drying-A review .Cocoa Grower's Bulletin,31,5-41.

Doymaz,I. (2005) Sun drying of figs: An experimental study. Journal of Food Engineering 71:403-407

Doymaz, I., Tugrul, N. and Pala, M. (2005) Drying characteristics of dill and parsley leaves. Journal of Food Engineering, 65: 421-428.

Doymaz, I. (2007a) Convective drying kinetics of strawberry. http://www.aseanfood.info/Articles/11023619.pdf. 916,917. Retrieved on 7th March, 2010.

Doymaz,I. (2007b) The kinetics of forced convective air –drying of pumpkin slices. Journal of Food Engineering 79:243-248.

Duncan,R. J. E., Godfrey G., Yap, T. N., Pettipher, G. l. and Tharumarajar T.,(1989) Improvement of Malaysia Cocoa bean flavor by modification of harvesting, fermentation and drying method. The Sime-Cadbury process. The planter 65:157-173.

Djokoto, I. K., Mauren, R. and Wuchi, B. (1989) A solar tunnel dryer for drying paddy. Journal of Agricultural Mechanization in Africa,Asia and Latin America. 20.(3) .

Ekechukwu, O. V. (1999) Review of solar-energy drying systems I: an overview of drying principles and theory. Energy Conversion and Management 40:593-613

Earle, R.L. (1983) Unit operation in food processing. Pergamon Press: 85-103.

Erenturk, S., Gulaboglu, M. S. and Gultekin, S. (2004) The thin layer drying characteristics of rosehip. Biosystems Engineering, 89 (2):159-166.

El-Beltagy, A., Gamea G. R., and Amer-Essa A. H. (2007) Solar drying characteristics of strawberry. Journal of Food Engineering 78 : 456-464.

Faber, E.A. (1961) The use of Solar Energy in heating water. Proceedings of United Nations Conference on New Sources of energy Volume 5: 29.

Faborede, M.O and Oladosu, F.A (1991) Development of cocoa pod processing machine. The Nigerian Engineer 26(4): 26-31.

FAO (2006). FAOSTAT Statistics Division of the Food and Agriculture Organization.http://faostat.fao.org.

Fellows P., (1988) Food Processing Technology, Ellis Horwood, Chichester: 281-294.

Fellows, P.J. (1990) Food Processing Technology. Principles and practice. Ellis Horwood Ltd. England: 281-311.

Fotso, J., Lecomte, D., Pomathios, L., and Nganhou, J. (1994) Convective drying of cocoa beans:Drying curves for various external conditions.Drying '94,Gold Coast ,Australia,937-994.

Fuller, R. J., Mollah, N.R. and Hayes R.J. (1994) A rotary tray system for a solar fruit dryer . Journal of Agricultural Mechanization in Africa,Asia and Latin America. 25 (4): 45-48.

Garba, B., Atiku, A. T., and Sambo, A. S. (1997) Comparative studies on the performance of two passive solar dryers in tropical area. Sokoto Energy Research Centre, Usman Dan Fodio University, Sokoto And Abubakar Tafawa Balewa University, Bauchi, Nigeria. Journal of Renewable Energy 5(1,2):112-118.

Garg H.P. (1982) Treatise on solar energy vol. (1) Fundamentals of solar energy .John Wiley: 50-52 337-339

Goyal, R. K., Kingsly, A. R. P., Manikantan, M. R., and Ilyas, S. M. (2007) Mathematical modeling of thin layer drying kinetics of plum in a tunnel dryer. Journal of Food Engineering 79:176-180.

Grow cocoa (2004) Global research on cocoa –working with and for farmers.

Gregoire, R. G. (1984). Understanding Solar Food Drying. Volunteer in Technical Assistance, Virginia. Retrieved from Url; http;//www.ecaliburaust.com.

Guyer, E.C. (1989) Handbook of Applied Thermal design. McGraw-Hill book co., New York: pg 8-12-42.

Habou, D., Asere, A. and Aihassan, A. M.,(2003) Comparative study of the drying rate of Tomato and pepper using forced and natural convention solar dryers. Nigerian Journal of Solar Energy 14:36-40.

Hall, C.W.(1980) Drying and storage of agricultural crops. The AVI Publishing Company, Connecticut,USA:1-15.

Haque, M. N., and Langrish,T.A.G.(2005). Assessment of the Actual Performance of an Industrial Solar Kiln for Drying Timber. Drying Technology 23:1541-1553.

Herbert, A., Budyko, U. and Ilo, S.(1984) Specification of drying of agricultural product. Retrieved from url:http://www.wet.utwente.nl/ssade/contents.htm.

Henderson, S.M. and Pabis (1961) Grain drying theory 1, Temperature effect on drying coefficient. Journal of Agric Engineering Research 6(3): 169-174.

Henderson S.M. (1972) Progress in developing the thin-layer equation. Transactions of the American Society Agricultural Engineering, Vol.17 (6) : 1167-1172.

Hll,C.L,Law C.L.,Cloke M.(2008) Modeling of thin layer drying kinetics of cocoa beans during artificial and natural drying .Journal of science and technology Vol.3 no 1:1-10

http://www.unido.org Classification of driers. Retrieved on 5th March, 2010

Hil, C. L. and Rabdul, R. (2006) Quality of Cocoa beans dried using a direct solar dryer at different loadings. Journal of Science of Food and Agriculture.86:1237-1243.

Hil, C. L. (2004) Cocoa Drying.Dehyrdation of products of Biological Origin .Science publishers,Enfield,NH,USA.

http://www.eurococoa.com. Cocoa story Cocoa as raw material.

Ikejiofor J. D. (1985) Passive solar dryer for drying Agricultural produce. Proceeding of the work shop on the physics and technology of solar energy conversion held at the University of Ibadan, Nigeria. : 158-159.

International Labour Organisation (1986) Solar drying: Practical method of food preservation. International labor organization publication Geneva, Switzerland: 1-12.

Jayas, D. S., Cenkowski, S., Pabis, S. and Muir, W. E., (1991) Review of thin layer drying and wetting equations, Drying Technology 9(3), Vol. 3 :551-588.

Jinap,S. (1994) Organics acids in cocoa beans- A review.asean Food Journal,9 (1),3-12

Kaleemullah,S.and Kailappan,R. (2005) Modeling of thin-layer drying kinetics of red chilies.Journal of Food Engineering 76 (4):531-537.

Karathanos, V. T. (1999) Determination of water content of dried fruits by drying kinetics Journal of Food Engineering 39:337-344.

Kashaninejad,M.,Mortazavi,A.,Safekordi,A.and Tabil,L.G.(2007). Thin-layer drying characteristics and modeling of pistachio nuts. Journal of Food Engineering 78:98-108.

Kenten, R. H and Allision, H. W. S. (1964) Mechanical drying of cocoa. Journal of tropical Agriculture 41 : 115-120.

Kingsly, A. R. P.and Singh D. B., (2007) Drying kinetics of pomegranate arils. Journal of Food Engineering,79 :741-744.

Kingsly, A. R. P. Rajbir Singh, R.K. Goyal and Singh D. B., (2007) Thin layer Drying behavior of organically produced Tomato.American Journal of food Technology 2:71-78

Kongdej L. and Songchai, W. (2009) Drying Kinetics of Steamed Glutinous Rice with a Free Convective Solar Dryer. Walailak J. of Sci. & Tech., 219.

Lahsasni,S.,Kouhila,M.,Mahrouz,M.and Jaouhari J.T. (2004) Drying kinetics of prickly pear fruit (Opuntia fiscus indica).Journal of Food Engineering 61:173-179

Lawand, T.A. (1966) A conference paper on solar cabinet dryer. Brace research Institute of Mc Gill University Monkeal, march 21-23: 158-164.

Lope, A.S (1984) The cocoa put soft drinks in Brazil and its effect on bean fermentation. Proceedings of 9th International cocoa research conference Lome, Togo, February 12-18: 511-514.

Madlopa,A.and G.Ngwalo. (2007) Solar dryer with thermal storage and biomass-back up heater. Solar Energy, 81(4):449-462.

Midilli, A., Kucuk, H. and Yapar, Z (2002) A new model for single layer drying. Drying Technology,20(7),: 1503-1513.

Midilli A. and Kucuk H. (2003) Mathematical modeling of thin layer drying of pistachio by using solar energy. Energy Conversion management 44,(11):11-22

Mohammadi, A., Rafiee, S., Keyhani, A.and Emam-jomeh, Z. (2009) Moisture content modeling of sliced Kiwifruit (cv.Hayward) during drying. Pakistan Journal of Nutrition, 8 78-82.

Muhlbauer, W. (1986) Present status of solar crop drying. Energy in Agriculture, 5:121-137

Mujumdar,A.S.(1987) (Ed) Handbook of Industrial Drying ,Marcel Dekker, New York

Mustafa, I., Sopian, K. and Daud, W.R.W. (2009) Study of the Drying Kinetics of Lemon Grass. American Journal of Applied Sciences, 1071.

National Institute of Oceanography, (1996) Cabinet Solar dryer. Retrieved from Url:http://WWW.nio.organization\Solar

Nganhou,J.,Lecomte,D.and Durmargue,et P. (1992) Heat and mass transfer through a thick bed of cocoa beans under stationary and transient inlet conditions. Drying '92,Montreal,Quebec,Canada,1514-1523.

Olalusi A.P (2008) Design, construction and performance evaluation of an indirect solar dryer for shea nut.

Opeke, L.K. (1984) Tropical tree crops. John Wiley and sons limited, London,pp108-119.

Opeke, L.K. (1982) Optimizing economic returns (profit) from cocoa cultivation through efficient use of cocoa by products. Proceeding of 9th International cocoa research conference Lome, Togo, February 12-18: 489-493.

Okons, M.R., Narsimhan, G., Singh, R.K., and Lund D.B. (1992) (Eds.) Handbook of food Engineering,New York:Marcel Dekker.

Ozbek,B.and Dadali,G.(2007) Thin –layer drying characteristics and modeling of mint leaves undergoing microwave treatment. Journal of Food Engineering 83:541-549

Ozdemir, M. and Devers, Y.O. (1999) The thin layer drying characteristics of hazelnuts during roasting. Journal of Food Engineering, 42:225-233.

Panchariya, P.C., Popovic, D. and Sharma, A.L. (2001). Modeling of desorption isotherm of black tea. Drying Technology 19 (6): 1177-1188.

Prachayawarakorn, S., Tia, W., Plyto, N. and Soponronnarit, S. (2008) Drying kinetics and quality attributes of low-fat banana slices dried at high temperature. Journal of Food Engineering, 85:509-517.

Rabiu,A.B (2003a). The Sun, our nearest star. A paper presented at the maiden Seminar of the Solar Terrestrial Physics Research Network on 20th August 2003, Federal University of Technology Akure :1-4.

Rabiu,A.B (2003b) Lecture notes on Energy Conversion and Storage Department of Physics, Federal University of Technology, Akure.

Rahman,M.S.,Perera,C.O. and Theband,C.(1998) Desorption isotherm and heat pump drying kinetics of peas. Food Research International 30:485-491

Rodrigues, S. and Fernades, F.A.N. (2007): Dehydration of melons in a ternary system followed by air-drying. Journal of Food Engineering 80:678-687.

Sabbah , M.A, Keener, H.M and Meyer, G.E. (1979) Simulation of solar drying of shelled corn using the logarithmic model. Transactions of the American Society Agricultural Engineering, 22(3):637-643.

Sacilik K. and Unal G. (2005) Dehydration Characteristics of Kastamonu Garlic Slices, Biosystems Engineering, 209.

Sacilik,K.,Keskin,R.and Elicin,A.K. (2006) Mathematical modeling of solar tunnel drying of thin layer organic tomato.Journal of Food Engineering 73:281-289.

Saeed,I.E.,Sopian,K. and Zainol Abidin,Z. (2006) Drying kinetics of Roselle (Hibiscus sabdariffa L.): dried in constant temperature and humidity chamber.Proc.SPS 2006.Edited by Muchtar. 29^{th} -30^{th} august.Permata,Bangi,S.D.E.,Malaysia :143-148.

Sahay, K.M. & Singh, K.K. (1994) Unit Operation of Agricultural Processing pp.109-113.

Scanlin, D. (1997) The design, construction and the use of an indirect through-pass solar food dryer, extracted from Home power magazine issue.No.57: 62-67

Senadeera, W., Bhandari, B. R., Young, G. And Wijesinghe B. (2003) Influence of shape of selected vegetable materials on drying kinetics during fluidized bed drying. Journal of Food Engineering 58(3):277-283.

ShahinRafiee, E. M., Keyhani, A. and Tabatabaeefar, A. (2009) Mathematical modeling of moisture content of Apple slices (Var.Golab) during drying. Pakistan Journal of Nutrition 8 (6):804-809.

Sharaf-Eldeen Y. I., Blaisdell J. L. and Hamdy M. Y. (1980) A model for ear corn drying. Transactions of the American Society Agricultural Engineering, 23: 1261– 1271

Sheng Yu, Z. (1990) Utilization of solar energy with far-infrared rays for drying animal feed. J.AMA. 21(1) : 67-68

Shivhare,U.S.,Gupta,A.,Bawa,A.S. and Gupta,P.(2000) Drying characteristics and product Quality of Okra.Drying Technology 18 (1-2):409-419.

Simpson,W.T.(1991) Dry kiln Operator's Manual.agriculture Handbook 188.edited by simpson,w.T.United State Department of Agriculture,Wisconsin,USA: 07-09.

Singh,B.,Panesar,P.S. and Nanda, V.(2006) Utilization of carrot pomance for the preparation of a Value Added Product.World Journal of Dairy and Food Sciences 1 (1) :22-27.

Singh, R.K., Lund, D.B. and Buelow, F.H. (1983) Application of Solar energy in Food Processing and Dehydration. Transactions of the American Society Agricultural Engineering, 26 (5) :1569-1573

Sogi,D.S.,Shivhare, U.S.,Garg,S.K and Bawa,S.A.(2003) Water sorption isotherms and drying characteristics of tomato seeds.Biosystems Engineering 84 (3) :297-301.

Spieyed, M.R. (1992) Schaum's outline of theory and problems of statistics, 2nd edition in S.I. units. McGraws-Hill book co, London: 264-371.

Sunseed Desert Technology (2003) Solar Drying: Drying Food with the energy of the Sun. Retrieved from Url.www.Sunsed.organization.uk.

Tarigan, E., Prateepchaikul, G., Yamsaengsung, R., Sirichote, A. and Tekasakul,p. (2007) Drying characteristics of unshelled kernels of candle nuts. Journal of Food Engineering 79: 828-833.

Thakor, N. J., okhansanj, S., F. W. and Yannacopoulos, S. (1999) Mass and dimensional changes of single canola kernels during drying .Journal of Food Engineering 40:153-160.

Thomson, T. L., Peart, P.M., and Foster, G.H. (1968) Mathematical simulation of corn drying: A new model. Transactions of the American Society Agricultural Engineering, 11:582-586.

Togrul I. T. and Pehlivan, D. (2002) Mathematical modeling of solar drying of apricots in thin-layers. Journal of Food Engineering, 55:209-216.

Togrul, I. T. and Pehlivan, D. (2004). Modeling of thin layer drying kinetics of some fruits under open air sun drying process. Journal of Food Engineering 65 (3) : 413-425.

Tuntiwaranuruk, U. and Mani, M. (2009) A thin layer drying model of chilli. 35th Congress on Science and Technology of Thailand, http://www.scisoc.or.th/. Retrieved on 12th March, 2010.

Upadhyay, A., Sharma, H. K., and B. C. Sarkar, (2008) "Characterization and Dehydration kinetics of Carrot Pomace".Agriculture Engineering International :The CIGR Ejournal.Manuscript FP 07 35.Vol.X.February,2008.

Valdez, A. and Valdez, M. (1977) A cook book for Building a solar food dryer. Sangre de cristo printing Alamosa.co.

Vietnam Institute of Agricultural Engineering (1998) Solar Drying of fish and shrimps. Retrieved from url:http:/www.epsea.org.html.

Verma, L.R., Bucklin, R.A., Endan, J.B. and Wratten, F.T. (1985) Effects of drying air parameters on Rice drying models. Transactions of the American Society Agricultural Engineering, 28: 296-301.

Wang C. Y. and Singh R. P. (1978) A single layer drying equation for rough rice. American Society Agricultural Engineering,paper No. 78-3001, St. Joseph, MI, USA

Wang, Z., Sun, J., Liao, X., Chen, F., Zhao, G., Wu, J. and Hu, X. (2007) Mathematical modeling on hot air drying of thin layer apple pomace.Food Research International 40:39-46.

Wan Daud, W. R., Meor Talib, M. Z. and Ibrahim, M. H. (1996) Characteristic Drying Curves of cocoa beans.Drying Technology,14 (10),2387-2396.

Wood, G.A.R. (1975) Tropical Agriculture Series, 3rd edition. Longman, London.

White, G. M., Bridges, T. C., Gewer, O. J. and Ross, I. J. (1978) Seed coat damage in thin layer drying of soybeans as affected by drying conditions. American Society Agricultural Engineering, paper No.3052.St Joseph (MI):

Yadollahinia A.R., Omid M. and Rafiee S. (2008) Design and Fabrication of Experimental Dryer for Studying Agricultural Products, International Journal of Agriculture & Biology , http://www.fspublishers.org/ijab/pastissues/IJABVOL_10_NO_1/11.pdf. 62, 63. Retrieved on 6th March, 2010.

Yagcioglu, A., Degirmencioglu, A. and Cagatay, F. (1999) Drying characteristics of laurel leaves under different conditions .In Bascetincelik, A. editor. Proceedings of the seventh International Congress on Agricultural Mechanization and Energy. Adana, Turkey: Faculty Of Agriculture, Cukurova University:565-569.

Yaldyz O. and Ertekin, C. (2001) Thin Layer Solar Drying of some vegetables. Drying Technology 19: 583-596

Yaldyz O., Ertekyn, C. and Uzun, H. B. (2001) Mathematical modeling of Thin Layer Solar Drying of sultana grapes. Energy, 26: 457-465.

Zhang, Q. and Litchfield, J.B. (1991) An optimization of intermittent corn drying in a laboratory scale thin layer dryer. Dry Technology;9:383-395

APPENDIX

Table 4.1 the cut test for solar drier

	1st batch	2nd batch	3rd batch
No of mouldy beans	7beans	7 beans	6 beans
% of mouldy beans	2.5	2.5	2.0
No of slatey beans	6 beans	7 beans	6beans
% of slatey beans	2.0	2.5	2.0
Germinated & other defects	6 beans	6 beans	7 beans
% Germinated & other defects	2.0	2.0	2.5
Weight of 300 beans	324g	310g	298g
Number of beans per 100g	85 beans	98 beans	102 beans
Loading density	2.97g/cm2	3.21g/cm2	3.97g/cm2
PH	6.00	5.50	5.50
Remark	Grade 1(main crop)	Grade 1(main crop)	Grade 1(Light crop)

Table 4.2 the cut test for open sun drying

	1st batch	2nd batch	3rd batch
No of mouldy beans	7beans	7 beans	6 beans
% of mouldy beans	2.5	2.5	2.0
No of slatey beans	6 beans	7 beans	6beans
% of slatey beans	2.0	2.5	2.0
Germinated & other defects	6 beans	6 beans	7 beans
% germinated & other defects	2.0	2.0	2.5
Weight of 300 beans	326g	314g	290g
Number of beans per 100g	86 beans	99beans	108 beans
Loading density	2.97g/cm2	3.21g/cm2	3.97g/cm2
PH	5.00	4.80	4.50
Remark	Grade 1(main crop)	Grade 1(main crop)	Grade 1(Light crop)

$$Loading\ density = \frac{Amount\ of\ cocoa\ beans}{dimension\ of\ the\ tray}$$

	Sun	Solar	Sun	Solar	Sun	Solar	Sun	Solar	Sun	Solar
Day (s)	Initial MC (%)	Initial MC (%)	Final MC (%)	Final MC (%)	Wt of water removed (kg)	Wt of water removed(kg)	Drying time	Drying time	Rate of drying (kg/hr)	Rate of drying (kg/hr)
1^{st}	56.06	56.06	39.120	39.511	0.555	0.548	4	4	0.139	0.137
2^{nd}	38.737	38.965	29.690	29.006	0.200	0.218	6	6	0.033	0.036
3^{rd}	29.464	28.776	27.598	27.062	0.030	0.036	6	6	0.005	0.006
4^{th}	25.883	26.142	19.033	17.006	0.134	0.147	4	4	0.034	0.368
5^{th}	17.353	13.152	11.688	10.408	0.080	0.079	4	4	0.020	0.020
6^{th}	10.970	8.922	9.498	6.500	0.026	0.042	6	6	0.004	0.007
7^{th}	8.744		7		0.018		6		0.003	

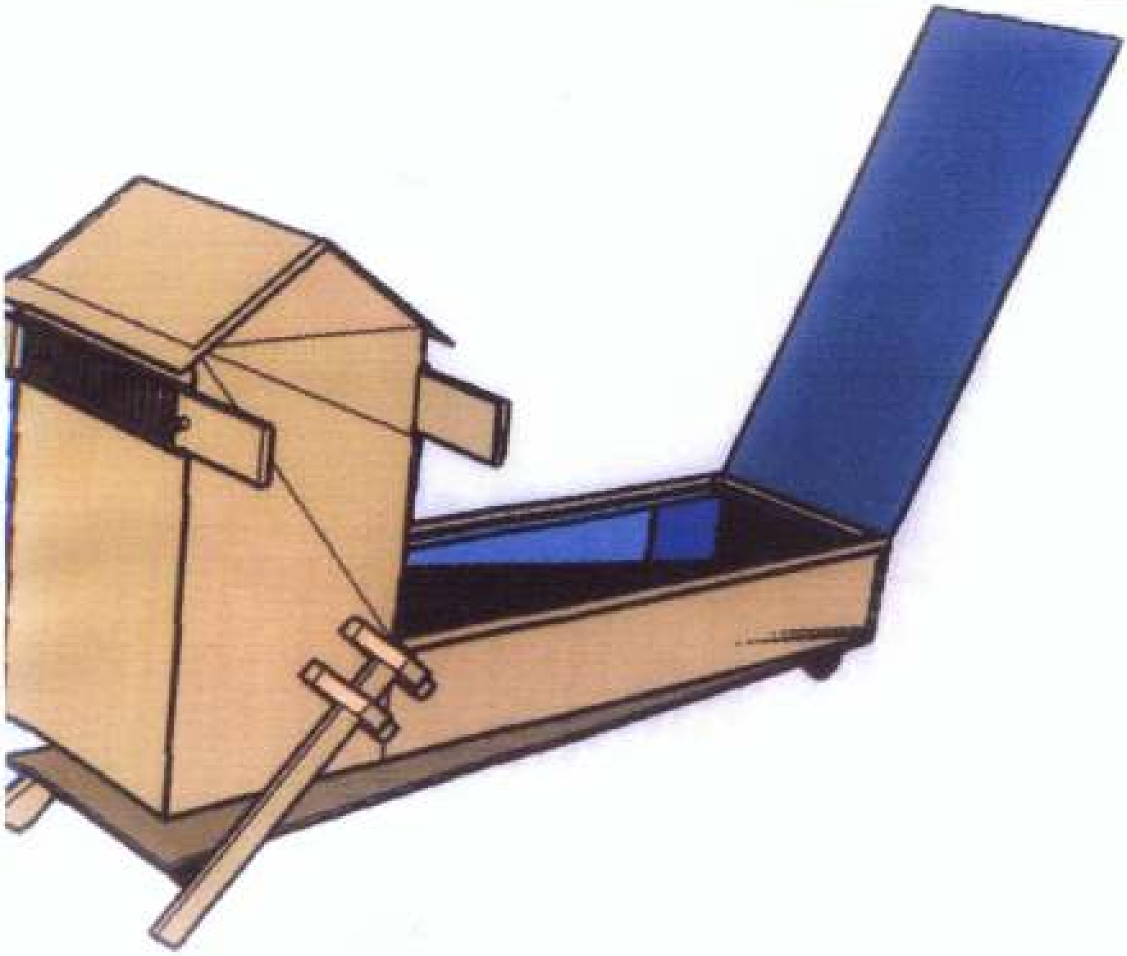
Table 4.8 DRYING OF COCOA BEANS BATCH TWO

	Sun	Solar	Sun	Solar	Solar	Sun	Sun	Solar	Solar	Sun
Day (s)	Initial MC (%)	Initial MC (%)	Final MC (%)	Final MC (%)	Wt of water removed (kg)	Wt of water removed(kg)	Drying time	Drying time	Rate of drying (kg/hr)	Rate of drying(kg)
1^{st}	56.17	56.17	46.799	46.512	0.197	0.196	5	5	0.394	0.392
2^{nd}	45.380	43.646	34.058	32.472	0.187	0.174	8	8	0.023	0.022
3^{rd}	33.687	31.791	22.688	17.960	0.126	0.108	7	7	0.018	0.015
4^{th}	21.529	12.983	12.486	7.000	0.069	0.074	4	4	0.017	0.019
5^{th}	12.486		7.500			0.019	3			0.006

Table 4.9 DRYING OF COCOA BEANS BATCH THREE

Days	Solar	Sun	Solar	Sun	Solar	Sun	solar	Sun	Solar	Sun
Day (s)	Initial MC (%)	Initial MC (%)	Final MC (%)	Final MC (%)	Wt of water removed (kg)	Wt of water removed(kg)	Drying time	Drying time	Rate of Drying (kg/hr)	Rate of Drying (kg/hr)
1^{st}	56.055	56.055	39.302	44.670	0.154	0.106	6	6	0.026	0.018
2^{nd}	40.614	41.250	21.806	31.810	0.098	0.076	6	6	0.016	0.013
3^{rd}	20.100	29.500	6.5	19.354	0.047	0.051	6	6	0.008	0.009
4^{th}	18.146				7.000	0.036		5		0.007

	MR PREDICTED	MR EXP SOLAR	Mr sun
	1.004	1	1
2	0.826225	0.913899	0.90708
3	0.784869	0.814492	0.795206
4	0.756413	0.726069	0.729526
5	0.733979	0.666156	0.659306
6	0.715131	0.655136	0.65289
7	0.5316	0.643044	0.645102
8	0.525125	0.532911	0.54133
9	0.518791	0.503341	0.52268
10	0.512587	0.474703	0.500259
11	0.506505	0.455328	0.47933
12	0.500537	0.454171	0.464644
13	0.494677	0.449528	0.461211
14	0.405544	0.44368	0.456608
15	0.400913	0.435414	0.449649
16	0.396325	0.427052	0.442621
17	0.391778	0.417377	0.435524
18	0.38727	0.414938	0.434334
19	0.382801	0.396385	0.418691
20	0.295947	0.370908	0.383829
21	0.292077	0.35784	0.283213
22	0.288226	0.212019	0.265616
23	0.284395	0.134238	0.244594
24	0.280581	0.120274	0.210436
25	0.276786	0.098904	0.197661
26	0.133883	0.078857	0.123774
27	0.130588	0.048881	0.09528
28	0.127302	0.019861	0.080686
29	0.124023	0.011967	0.062106
30	0.120751	0.006003	0.062106
31	0.117488	0	0.058344
32	0.05993		0.062106
33	0.056793		0.050774
34	0.053661		0.035444
35	0.050535		0.023778
36	0.047414		0.019857
37	0.044299		0.015919



A CONVECTIVE SOLAR DRYER