THIN LAYER DRYING CHARACTERISTICS OF AMARANTH GRAINS IN A NATURAL CONVECTION SOLAR TENT DRYER

ERICK KIPLANGAT RONOH

MASTER OF SCIENCE

(Agricultural Processing Engineering)

JOMO KENYATTA UNIVERSITY OF

AGRICULTURE AND TECHNOLOGY

2010

Thin Layer Drying Characteristics of Amaranth Grains in a Natural Convection Solar Tent Dryer

Erick Kiplangat Ronoh

A thesis submitted in partial fulfillment for the degree of Master of Science in Agricultural Processing Engineering in the Jomo Kenyatta University of Agriculture and Technology

2010

DECLARATION

This thesis is my original work and has not been presented for a degree in any other University.

Signature: -------------------------------------- Date: -------------------------------

Erick Kiplangat Ronoh

This thesis has been submitted for examination with our approval as University Supervisors.

Signature: -------------------------------------- Date: -------------------------------

Dr. Christopher L. Kanali

JKUAT, Kenya

Signature: -------------------------------------- Date: -------------------------------

Dr. Joseph T. Mailutha

JKUAT, Kenya

Signature: -------------------------------------- Date: -------------------------------

Prof. Douglas Shitanda

JKUAT, Kenya

DEDICATION

To my dear Mum and Dad.

For their role in bringing me up, supporting me at any cost, and teaching me that all things are possible.

ACKNOWLEDGEMENT

Foremost, I thank the Almighty God for providing me with an amicable and peaceful working atmosphere to pursue my academic dreams. I deeply acknowledge the efforts and guidance of my supervisors Dr. Christopher L. Kanali, Dr. Joseph T. Mailutha and Prof. Douglas Shitanda. I have greatly appreciated their ability to approach complex problems with simple physical intuition and clever experimental techniques, and I have grown enormously through these experiences. I gratefully acknowledge the financial support by grants from Jomo Kenyatta University of Agriculture and Technology (JKUAT) and German Academic Exchange Service (DAAD).

I also acknowledge the support I received from other staff members of Biomechanical and Environmental Engineering Department (BEED) and appreciate the benefits of working in such a thriving academic environment. I am also grateful for the expertise and technical assistance given by Mr. P. Mulyungi of Horticulture Department (JKUAT), and Messrs P. Karanja and D. Votha of Food Science and Technology Department (JKUAT). Special recognition goes to my colleagues (Messrs Mayunzu, Kamami, Karara, Kang’au and Kituu) for their encouragement, support and company during my studies.

Most importantly, I thank my family members and friends for their support, love, understanding, excitement and prayers during my studies, particularly during the drafting of this thesis. To all of you I say **“*Ahsante sana*”** and may God bless you abundantly.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

LIST OF APPENDICES

LIST OF ABBREVIATIONS AND SYMBOLS

a,b,c,n	Coefficients in drying models
a*	Colour parameter, green-red spectrum
A	Energy collection area (m^2)
$\mathbf{A_z}$	Solar azimuth angle (degrees)
b*	Colour parameter, blue-yellow spectrum
C	Diffuse radiation factor
CP	Crude protein
$\mathbf{C_{pa}}$	Specific heat capacity of air (J/kg-K)
$\mathbf{C_{pw}}$	Specific heat capacity of water vapour (J/kg-K)
$\mathbf{d_{av}}$	Average diameter (m)
d.b	Dry basis
$\mathbf{D_e}$	Effective moisture diffusivity (m^2s^{-1})
f	Factor of standard HCL solution (approximately 1)
$\mathbf{h_{fg}}$	Latent heat of vapourization
h*	Hue angle (degrees)
H	Humidity ratio of air (kg water/ kg dry air)
$\mathbf{H_r}$	Hour of the day in 24 hour time
i,j,l	Nodal indices
$\mathbf{I_b}$	Direct solar radiation (W/m^2)
$\mathbf{I_d}$	Diffuse solar radiation (W/m^2)
$\mathbf{I_{sc}}$	Solar constant, which is valued at 1367 W/m^2
$\mathbf{I'_{sc}}$	Solar energy flux on the earth's surface at the n^{th} day of the year (W/m^2)
$\mathbf{I_t}$	Total solar radiation (W/m^2)

k	Drying rate constant (h^{-1})
L*	Colour parameter, light-dark spectrum
m_a	Mass flow rate of air (kg/s)
M	Moisture content at time t hours (% dry basis)
M_e	Equilibrium moisture content (% dry basis)
M_o	Initial moisture content (% dry basis)
MR	Moisture ratio
$MR_{act,i}$	Actual moisture ratio
$MR_{pre,i}$	Predicted moisture ratio
n	Day of the year
n_c	Number of constants
N	Number of observations
N_s	Normality of standard hydrochloric acid solution
PF	Protein factor
PVC	Polyvinyl chloride
Q_a	Useful energy absorbed by the drying air and the material being dried (W)
Q_i	Heat energy incident on the collector surface (W)
Q_v	Heat of vapourization of moisture from the material (W)
Q_L	Energy losses which (W)
$Q_{s(a,h)}$	Sensible heat of the air and humidity inside the dryer (W)
r_a	Radius of amaranth seed (m)
Rh_a	Relative humidity in the open sun (%)
Rh_i	Relative humidity in the solar tent dryer (%)
R^2	Coefficient of determination

RMSE	Root mean square error
S	Weight of sample taken (g)
t	Drying time (hours)
T_a	Ambient temperature (^oC)
T_i	Temperature developed in the solar tent dryer (^oC)
ΔT	Temperature difference (K)
U	Overall energy loss coefficient (W/m^2-K)
V	Volume of diluted digest taken for distillation (ml)
V_1	Titre for sample (ml)
V_2	Titre for blank sample (ml)
W_d	Dry weight (g)
W_t	Wet weight (g)
x,y,z	Plane coordinates in the solar tent dryer
β	Angle of inclination of surface from horizontal (degrees)
δ	Angle of declination (degrees)
ε	Absolute residual error (%)
η_p	Prediction performance (%)
Φ_s	Sphericity
ρ_e	Bulk density (kg/m^3)
ρ_p	True density (kg/m^3)
φ	Latitude (degrees)
τ	Transmissivity of the cover material (%)
ω	Hour angle (degrees)
χ^2	Reduced chi-square

LIST OF PUBLICATIONS

ABSTRACT

Amaranth plants are indigenous in most semi-arid areas of Kenya. However, the communities in these areas are ignorant of the importance of the grains from these plants in their contribution to health and food security. Amaranths are susceptible to partial shatter losses especially when harvested at a moisture content less than 30% dry basis (d.b). Thus harvesting must be done at moisture content of 30% d.b or higher which requires necessary artificial drying to safe storage moisture level. The grains are traditionally dried in thin layers under the open sun. The open sun drying has disadvantages such as lack of temperature control, intensive labour and contamination from dust, foreign materials, rodents and bird droppings. A natural convection solar tent dryer would be a useful drying technique for safe preservation of these grains. This study aimed at analyzing thin layer drying characteristics of amaranth grains in a natural convection solar tent dryer. More specifically, temperature distribution in the dryer and the effect of colour of cover material of the dryer on thin layer drying of the grains were studied. The study also focused on modeling the thin layer solar drying process and determining the effect of the cover material on hardness, colour and crude protein content of the grains.

The distribution of temperature was analyzed using nine discrete points spread in two planes in the dryer. The effect of colour of cover material was determined by drying the grains in experimental dryers with different coloured PVC materials. Drying of grains in the actual dryer (1.85 m wide, 2.73 m long and 2.55 m high) was carried out at two levels (Layers 1 and 2). Thereafter, non-linear regression analysis was conducted to evaluate the performance of six thin layer drying models (viz., Newton, Page, Modified Page, Henderson & Pabis, Logarithmic and Wang & Singh) for amaranth grains. The models were compared using the coefficient of determination (R^2), root mean square error (RMSE), reduced chi-square (χ^2) and prediction performance (η_p). Finally, the grains that were dried under different cover materials were evaluated for hardness, colour and crude protein content.

An analysis of variance at 5% level of significance showed that there was no significant difference in temperature distribution within and between the planes. In addition, the results showed that the dryer with the clear cover material achieved highest temperatures (44.5±5.8°C) and drying rates, and lowest relative humidity values (23.5±6.5%) as compared to those with yellow and nectarine diffused materials. However, the temperatures and relative humidity values were found not to be significantly different. Further, the results indicate that the grains dried in the solar tent dryer attained an equilibrium moisture content of 7% d.b from an initial one of 61.3–66.7% d.b after 4.5 hours of drying as opposed to 7 hours for the open sun. There was no significant difference in drying rates when the grains were dried in Layers 1 and 2 of the dryer. The Page model best described thin layer drying of the grains, attaining the highest R^2 (0.994–0.999) and η_p (80.0–88.2%), and the lowest RMSE (0.0003–0.0240) and χ^2 (0.0000–0.0154) values. Finally, the results showed that there was no significant difference on hardness, colour and crude protein content of the grains dried under different cover materials and the open sun. The results therefore demonstrate that natural convection solar tent dryers can be utilized to enhance drying of amaranth grains in layers without significantly affecting their physical, optical and nutritive properties.

CHAPTER ONE

1.1 INTRODUCTION

1.1.1 Background

The need for diversified food production in semi-arid areas of Kenya calls for the promotion of indigenous crops. The main constraint, however, involve the selection of suitable crop varieties which are drought tolerant and of high productivity. Solutions should therefore be sought to enhance food sufficiency and poverty alleviation. One such solution is promoting the use of amaranth grains by small scale farmers in such dry areas. Amaranth grows vigorously, tolerates drought, heat, and pests, and adapts readily to a wide range of environments (Prim, 2003; Abalone *et al*., 2004). In addition, amaranth's great nutritional qualities are the driving force facilitating its promotion. It is high in protein (16–18%), particularly in the amino acid, lysine, which is low in the cereal grains (Abalone *et al*., 2004; Gonzalez *et al*., 2002). The high productivity (1000–3000 kg/ha) of amaranth fosters food security and high economic returns (Prim, 2003).

Amaranths are susceptible to partial shatter losses during harvest, especially, when their moisture content in the field is less than 30% dry basis (d.b) (Prim, 2003; Gupta, 1986). Storage of this grain at a moisture content that is higher than the equilibrium moisture level of about 10% d.b leads to mould growth and renders the grain unfit for human consumption (Abalone *et al*., 2006; Weber, 1987). To ensure safe preservation of amaranth grains, they must be dried to equilibrium moisture content which requires good drying techniques. These grains are mostly dried in the rural areas in thin layers either in the open sun or in a solar dryer (Abalone *et al*., 2004). Thin layer drying is the process of removal of moisture from a porous media by evaporation, in which drying air is passed through a thin layer of the material until the equilibrium moisture content is reached (Omid *et al*., 2006). At present most crops produced in rural areas of developing countries like Kenya are dried using the open sun drying method (FAO, 1994; Bateman, 1994). Open sun drying, however, has disadvantages such as lack of temperature control, intensive labour and contamination from dust, foreign materials, rodents and bird droppings (Basunia and Abe, 2001; Inprasit and Noomhorm, 2001). The best alternative, especially when amaranth is produced on commercial basis, is to provide affordable drying methods such as a natural convection solar tent dryer. This type of solar dryer is affordable in the rural set-up, saves labour, ensures good quality of material being dried, and facilitates faster drying of grains especially under favourable conditions (Whitfield, 2000).

A considerable amount of work has been reported concerning thin layer drying of grains and other agricultural products, but very little information is available on amaranth (Pagano and Mascheroni, 2005; Abalone *et al*., 2004). Thin layer drying studies were therefore carried out to understand the drying characteristics of amaranth grains and to obtain proper drying models which can explain thin layer drying process of these grains. The analyses relating the drying process, dried amaranth quality and the drying conditions (viz., temperature, relative humidity and solar radiation) in the open sun and in the solar tent dryer are useful in developing an appropriate drying technique and hence the interest in the present study.

1.1.2 Objectives

The overall objective of this study was to analyze thin layer drying characteristics of amaranth (*Amaranthus cruentus*) grains in a solar tent dryer under natural convection. The specific objectives were as follows:

1) To analyze the distribution of temperature in the solar tent dryer.
2) To determine the effect of colour of cover material on thin layer drying of amaranth grains.
3) To model thin layer solar drying of amaranth grains.
4) To determine the effect of colour of cover material on the physical, optical and nutritive properties of amaranth grains.

1.2 REVIEW OF LITERATURE

1.2.1 Description of Amaranth

Amaranth (*Amaranthus cruentus*) is a common flowering plant species found in most parts of Africa and it yields the nutritious staple amaranth grain (Grubben and Denton, 2004). In Kenya this plant is indigenous in semi-arid areas with mean annual rainfall of about 250 mm. The *Amaranthus cruentus* species is one of the three *Amaranthus* species, the other two being *Amaranthus hypochondriacus* and *Amaranthus caudatus*, that are cultivated as a sources of grain for both human and animal consumption. Amaranth has several common names, including purple amaranth, red amaranth and Mexican amaranth. *Amaranthus cruentus* is a tall annual plant that has clusters of light yellow flowers as shown in Figure 1.1 (Abalone *et al*., 2006). The plant, usually green in colour, can grow up to two (2) m in height, and mostly blossoms in dry weather. It is believed to have originated from *Amaranthus hybridus*, with which it shares many morphological features such as single layer of cells, large, thick-walled endosperm cells and perisperm at the centre of the seed containing starch granules (Irving *et al*., 1981). Reports indicate that *Amaranthus cruentus* was in use as a source of food in Central America as early as 4000 BC (Abalone *et al*., 2006).

The potential of both grain and vegetable amaranth as a food resource has been reviewed extensively by many researchers (Saunders and Becker, 1985; Bressani, 1988). The increasing interest in amaranth by the international community in its growth and use lies in its seeds, which, in addition to carbohydrates, contain between 16 and 18% proteins, with a high lysine content (Abalone *et al*., 2006). Amaranth grain, produced on family scale, is exposed to ambient air and naturally dried. When amaranth is cultivated on a large scale (about 25 hectares), heavy field losses occur as the crop easily shatters the seeds when dry. To reduce the field losses, amaranth should be harvested at a moisture content of about 30% d.b or more and then artificially dried to reduce the moisture level to about 10% d.b for safe preservation (Weber, 1987).

Figure 1.1 Plate showing *Amaranthus cruentus* plants.

The grains of the light yellow domesticated *Amaranthus cruentus* are consumed as cereals. However, those of the black wild plant are considered as weed, hence are not edible (Abalone *et al*., 2006). In order to consume them, the grains are either ground into flour, popped like popcorn, cooked into porridge or made into a confectionery called *alegría*. The seeds, which are lens-shaped and are about one millimeter in diameter, can be germinated into nutritious sprouts which can be used on sandwiches and in salads. None of the common grains such as beans or maize contain adequate amounts of lysine to meet human dietary needs. In addition, some people with food allergies have used amaranth as a substitute for other grains. It is 90% digestible which makes it a good food for those recovering from illness because the body will absorb most of its nutrients. Amaranth has also been tested for use in cereals, breads, pancake mixes, pastas and snack foods in combination with wheat and corn (Weber, 1987). It has been noted that blends of amaranth and corn, or amaranth and whole wheat, provide a protein that is as good as that in milk. Post-harvest practices are very important for maintaining high quality grain. Further, amaranth is at times used as an ornamental plant while the leaves are consumed as vegetables when cooked (Abalone *et al.*, 2006). While *Amaranthus cruentus* is no longer a staple food in most countries of origin, it is presently grown and sold as a health food in most semi-arid regions of Africa (Grubben and Denton, 2004; Calzetta Resio *et al.*, 2005). Hence, it is an important crop for subsistence farmers living in dry regions of Africa (including Kenya) who often face food insecurity.

According to Lost Crops of Africa (2006), as a traditional food crop in Africa, amaranth has potential to improve nutrition, boost food security, foster rural development and support sustainable land conservation. It has also been reported that amaranth is affordable and can be cultivated by indigenous people in rural areas for several reasons (Abalone *et al.*, 2006; Prim, 2003). Foremost the crop can easily be harvested manually, it produces a lot of seeds which are used as grain, and it is highly tolerant to harsh arid environments which are typical of most subtropical and some tropical regions. In addition, the seeds have large amounts of protein and essential amino acids (such as lysine) which is usually deficient in plant protein and makes amaranth an effective agent against cancer and heart disease. Due to its weedy life history, amaranth grows very rapidly and its large seed head can weigh as much as one kilogram containing about a half-million seeds (Prim, 2003). *Amaranthus* species are reported to have a 30% higher protein value than other cereals, such as rice, wheat, oats and rye (Tucker, 1986). The foregoing information shows that amaranth is a potentially valuable traditional crop that could be promoted to enhance food security, health and improve rural income for the inhabitants living in the semi-arid regions of Africa.

1.2.2 The Need for Grain Drying

Drying is defined as the removal of moisture from a product, and in most practical situations the main stage during drying is the internal mass transfer. Drying is one of the cheap and common preservation methods for biological products (Shitanda and Wanjala, 2003). Drying technology is an amalgamation of transport phenomena and material science since it deals not only with the removal of a liquid to produce a solid product but also with the extent to which the dried product meets the necessary quality criteria (Kudra and Mujumdar, 2002). At the beginning of the drying process, the drying rate is high and it decreases continuously with decreasing moisture content. Drying rate is defined as the amount of moisture removed per unit time during the drying period (Doymaz, 2005). The problems with grain drying will vary from year to year depending on weather conditions. It is important to remove as much vegetative material as possible from the grain at harvest time to reduce the potential sources for the introduction of mould and undesirable flavours.

Developing countries such as Kenya suffer heavy losses of grains in the post harvest period. The study of drying agricultural produce has been the subject of many researches (Brooker *et al*., 1992; Karim and Hawlader, 2004; Lahsasni *et al*., 2004). Direct grain losses are mainly caused by rodents, birds, spillage and contamination, and are often as high as 10–25% (Kristoferson and Bokalders, 1991; Nindo, 1995). In Kenya, for example, post harvest cereal grain losses range from 18–25% (Nindo, 1995). This high level of grain loss is of critical economic importance to countries such as Kenya that largely rely on agricultural produce for its foreign exchange. Grains require special treatment to prevent rapid decomposition and growth of fungi. Drying of crops after harvesting is an important preservation process. However, it is at this stage that much of the grain deterioration occurs due to improper drying techniques and equipment (Salunkhe *et al*., 1985).

Drying preserves grains by removing enough moisture from grain to prevent decay and spoilage. Moisture content of properly dried grain varies from 5 to 25% d.b depending on the type of grain. However, for amaranth the recommended moisture content for safe storage is about 10% d.b (Weber, 1987). Successful drying depends on: enough heat to draw out moisture, without cooking the grain; dry air to absorb the released moisture; and adequate air circulation to carry off the moisture. When drying grains, the key factor is to remove moisture as quickly as possible at a temperature that does not seriously affect the flavour, texture and colour of the grain. If the temperature is too low in the beginning, microorganisms may grow before the grain is adequately dried (Vizcarra-Mendoza *et al*., 2003). If the temperature is too high and the humidity is too low, the grain may harden on the surface. This makes it more difficult for moisture to escape and the grain does not dry properly.

Although drying is a relatively simple method of grain preservation, the procedure is not exact since there are different drying options to adopt such as open sun or solar drying methods. The type of product to be dried is an important factor to consider in all drying processes. This is because the physical and chemical properties of the product play a significant role during drying due to possible changes that may occur and because of the effect that such changes may have in the removal of moisture from the product (Ibarz and Barbosa-Canovas, 2003).

1.2.3 Solar Drying

1.2.3.1 Introduction

Traditionally, open sun drying has been used to dry grains as a means of preservation (Basunia and Abe, 2001). However, large-scale production limits the use of open sun drying. These limitations include lack of ability to control the drying process properly, weather uncertainties, high labour costs, large area requirements, insect infestation and contamination with dust and other foreign materials. Solar drying is fast becoming an important alternative for farmers in developing countries, such as Kenya, as the dryers can generate relatively high air temperatures and low relative humidity, both of which are conducive to improved drying rates (FAO, 1994; Whitfield, 2000). Solar energy is preferred in the tropics to other sources of energy because it is abundant, inexhaustible and non-polluting. It can be tapped at relatively low cost and has no associated environmental dangers. The other alternative sources of energy (oil, gas, wood or electricity) have adverse effects on the environment and are in most cases more expensive (Guine *et al*., 2007; Karekezi and Ranja, 1997). Mechanized systems using non-renewable fuel sources are expensive to run and although the solar heaters are simple, the technology behind them needs to be carefully explained so that they are constructed to operate efficiently.

The search for alternative sources of energy for drying and appropriate designs of dryers has been the subject of many researches (Al-Ajlan *et al*., 2003; FAO, 1994; Arinze, 1987). The introduction of solar dryers in rural areas can reduce crop losses and improve the quality of dried product significantly compared to traditional drying methods (Muhlbauer, 1986). Consumers of solar dried products are also willing to pay more for these products because they are of better quality compared to the open sun dried ones which are mostly contaminated and infested by insects and pests (Agribusiness Development Centre, 2001). In recent years, numerous attempts have been made to develop solar drying mainly for preserving agricultural products. The challenge still remains to be the effective and efficient utilization of solar drying for the benefit of small-scale farmers in the tropics (Guine *et al*., 2007).

1.2.3.2 Solar Dryer Classification

The classification of solar dryers is generally based on: whether or not the product is directly exposed to insolation, the mode of airflow through the dryer, and the temperature of air circulating in the chamber (Arinze, 1987). As per the exposure to insolation classification, solar dryers can further be classified as either direct or indirect. Direct dryers are those in which the material is exposed to the sun unlike in indirect dryers where it is placed in an enclosed drying chamber that shields the product (such as grain) from insolation. In direct solar dryers, heat transfer to the drying grain is by convection and radiation and therefore the rate of drying can be greater than for indirect dryers. There are two possible modes of air flow, natural convection or forced convection. The former is reliant upon thermally induced density gradients for the flow of air through the dryer whereas for forced convection dryers the air flow is dependent upon pressure differentials generated by a fan. Because of the higher airflow rates, solar collector efficiencies in forced convection dryers are relatively higher than in natural convection dryers (Duffie and Beckman, 1991; Saleh and Saker, 2002; Togrul and Pehlivan, 2002).

Although many drying systems are now available, it is still recognized that further research is needed to optimize designs, such as collector designs (Karim and Hawlader, 2004), to monitor and control the drying process (Oosthuizen, 1987), to increase the lifespan of materials used in their construction, to match individual dryers to different crops and climates (Brooker *et al.*, 1992; Steinfeld and Segal, 1986), and to give satisfactory performance with respect to energy requirements (Steinfeld and Segal, 1986). This study focused on the analysis of thin layer drying of amaranth grains in a direct solar dryer with natural convection, in order to model the drying process and to determine suitable dryer materials.

Drying characteristics of the particular materials being dried and simulation models are needed in the design, construction and operation of drying systems. Several researchers have developed simulation models for natural and forced convection solar drying systems (Diamente and Munro, 1993; Dinçer, 1996; Exell, 1980; Tiris *et al*, 1994; Zaman and Bala, 1989). There is need to determine temperature and moisture content distribution in grain dryers in order to monitor and control the drying process, for safe drying and product quality maintenance (Uluko *et al*., 2006).

1.2.3.3 Solar Grain Dryers

Amaranth grains are harvested at high moisture content (>30% d.b) (Vizcarra-Mendoza *et al*., 2003) and this necessitates the use of dryers to avoid the growing of microorganisms and the development of fungus, inhibit enzymatic reactions, minimize the loss of flavours and textures. Although commercial dryers have been used to dry grains (Kristoferson and Bokalders, 1991), they are unaffordable to small-scale farmers since the fuels (oil, gas, wood or electricity) required to generate heat for the drying process are very costly (Keener, 1991).

Solar grain dryers make use of the abundant solar energy and at the same time allow the production of dried grains of better quality, since the problems of contamination and infestation are minimized (Guine *et al*., 2007). These dryers must be properly designed in order to meet particular drying requirements of agricultural products and give satisfactory performance concerning energy requirements. The air entering the drying chamber of a solar grain dryer can either be at the ambient temperature or at some higher temperature; the elevation in temperature of the air being achieved by its passage through a solar collector prior to the drying chamber. Dryers that employ a separate solar collector and drying chamber have an inherent tendency towards greater efficiency as both units can be designed for optimum efficiency of their respective functions (Sacilik *et al*., 2006).

1.2.3.4 Quality Changes during Drying of Grains

The commonly examined properties of dried agricultural products may be classified into engineering properties and quality related properties (Krokida and Maroulis, 2000). The engineering properties are essential in the design of food processes and processing equipment, and in the efficient operation and control of processing plants. These properties include effective moisture diffusivity, effective thermal conductivity, specific heat, equilibrium moisture content, and viscosity (Krokida and Maroulis, 2000). Conversely, quality related properties are important for characterization and prediction of the quality of dried product, and for the development of new industrial products with desired properties or for quality improvement of existing ones. These properties can be categorized into (Krokida and Maroulis, 2000): structural properties (viz., density, porosity, pore size, specific volume), optical properties (viz., colour, appearance), textural properties (viz., compression test, stress relaxation test, tensile test), thermal properties (viz., state of product: glassy, crystalline, rubbery), sensory properties (viz., aroma, taste, flavour), nutritional characteristics (viz., vitamins, proteins), and rehydration properties (rehydration rate and capacity).

Several studies have been carried out to investigate the effect of drying temperature on quality attributes for different agricultural materials (Hii *et al*., 2009; Sacilik and Elicin, 2006; Sacilik *et al*., 2006). For instance, Hii *et al*. (2009) analyzed the effect of drying air temperature on such quality attributes as hardness, fracturability, colour and total polyphenols of dried cocoa beans. In real on-farm processing of agricultural products such as amaranth grains, much higher temperatures are used in order to increase the output of the dryer but this could have an adverse effect on dried product quality

(Hii *et al*., 2009). The analyses of quality related properties of amaranth grains as affected by drying temperatures in the solar dryers are scarce and consequently this calls for further studies (Abalone *et al*., 2004; Hii *et al*., 2009).

1.2.4 Application of Thin Layer Drying Models

Numerous mathematical models have been developed that describe the rate of moisture loss during the thin layer drying of agricultural and food products (Basunia and Abe, 2001; Abalone *et al*., 2006). Thin layer drying models mainly fall into three categories: empirical, semi-empirical and theoretical (Fortes and Okos, 1981). Based on test results, empirical models yield a direct relationship between moisture content and drying time, neglecting the fundamentals of the drying process. The Wang and Singh model (Wang and Singh, 1978) is an example of empirical model found in literature. The semi-empirical models are usually based on Newton's law of cooling as applied to mass transfer and isothermal drying. Theoretical models take into account different moisture transfer mechanisms and involve the solution of coupled or uncoupled heat and mass transfer equations.

Semi-empirical models have been used extensively to describe the drying characteristics of agricultural products in thin layers. These models offer a compromise between theory and ease of application (Akpinar, 2006). Examples of semi-empirical models are the Newton model, Page model, Modified Page model, Henderson and Pabis model and Logarithmic model. However, the Newton model assumes that resistance to moisture movement and thus gradients within the material are negligible (Colson and Young, 1990). Most semi-empirical drying models have been developed as a result of modification of the Newton model. For instance, the Page model is a modified empirical solution of the Newton model with a new empirical drying exponent *n*. The introduction of drying coefficients improves the performance of the model in predicting the thin layer drying process. Many investigators (Abalone *et al*., 2006; Basunia and Abe, 2001; Shatadal *et al*., 1990) have successfully used the Page model to describe the thin layer drying of various cereal grains and oil seeds. The Page model is convenient to use compared with the theoretical moisture transfer equation which takes more computing time in fitting the data and deep bed simulations. The Henderson and Pabis model is the simplest approximation to the well-known diffusion model, when only one term of the infinite series is used. The use of thin layer drying models is a valuable tool for prediction of performance of solar drying systems. The high level of accuracy of the thin layer drying models has also facilitated their application in deep bed simulation (Basunia and Abe, 2001).

This study focused on determining the efficacy of the models discussed above, as shown in Table 1.1, in the analysis of thin layer drying of amaranth grains in a solar tent dryer. The models have widely been applied to predict thin layer drying of agricultural products and they exhibit a decreasing drying rate (Akpinar, 2005). The drying parameters and coefficients in the individual models can be related to the drying conditions such as temperature, air velocity and relative humidity. Studies on modeling of the thin layer drying process of amaranth grains are relatively scarce compared to other cereal grains (Abalone *et al*., 2006) and hence the need for this study.

Table 1.1 Mathematical models widely used to describe the drying kinetics

Model no.	Model equation*	Name	Source
1	MR = exp($-kt$)	Newton	Liu and Bakker-Arkema (1997)
2	MR = exp($-kt^n$)	Page	Zhang and Litchfield (1991)
3	MR = exp[$-(kt)^n$]	Modified Page	Overhults *et al.* (1973)
4	MR = $a$exp($-kt$)	Henderson and Pabis	Chhninman (1984)
5	MR = $a$exp($-kt$) + c	Logarithmic	Yagcioglu *et al.* (1999)
6	MR = 1 + at + bt^2	Wang and Singh	Wang and Singh (1978)

* *a, b, c* and *n* are drying coefficients, *t* is drying time (hours) and *k* is drying constant (h^{-1})

CHAPTER TWO

2. THEORY

2.1 Model for Solar Radiation

Solar drying is a form of convective drying, in which the air is heated by solar energy in a solar collector. Solar energy is an important and economical source of renewable energy, particularly during energy crises, when the costs of fossil fuel and electricity increase (Saravacos and Kostaropoulos, 2002). The amount of solar energy reaching the earth's surface is expressed in terms of the solar constant, I_{sc}. The I_{sc} is valued at 1367 W/m^2 and is defined as the total radiation energy received from the sun per unit area in a unit time on the earth's surface perpendicular to the sun's rays at a mean distance (1.496×10^8 km) of the earth from the sun (Sukhatme, 2003). Due to the elliptical orbiting of the earth around the sun, the distance between the earth and the sun fluctuates annually and this makes the amount of energy received on the earth's surface to fluctuate in a manner given by equation (2.1), where I'_{sc} is the solar energy flux on the earth's surface at the n^{th} day of the year, n is 1 on 1^{st} January, and 366 on 31^{st} December.

$$I'_{sc} = I_{sc} * \left(1 + 0.033\cos\left(\frac{360n}{365}\right)\right) \qquad (2.1)$$

The direct solar radiation, I_b, reaching a unit area of a horizontal surface on the earth in the absence of the atmosphere (see Figure 2.1) can be expressed by equation (2.2) (Garg and Prakash, 2000; Al-Ajlan *et al*., 2003). In this equation, I'_{sc} is solar energy flux on the earth's surface at the n^{th} day of the year (W/m^2), φ is latitude (degrees), δ is angle of declination (degrees), ω is hour angle (degrees), and β is angle of inclination of the surface from horizontal surface of the earth.

$$I_b = I'_{sc}\left(\sin(\varphi\text{-}\beta)\sin\delta + \cos\delta\cos\omega\cos(\varphi\text{-}\beta)\right) \quad (2.2)$$

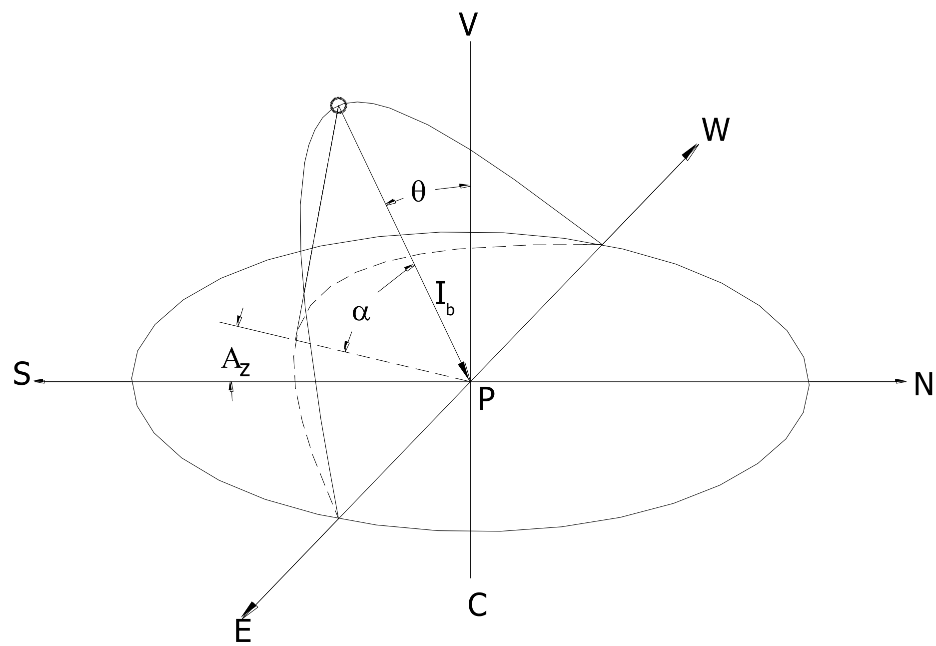

Figure 2.1 Solar angles in the apparent movement of the sun over the earth.

The angle δ can be evaluated from the expression presented in equation (2.3) (Sukhatme, 2003; Ezekoye and Enebe, 2006). On the other hand, ω is computed by equation (2.4) (Sukhatme, 2003), where H_r is the hour of the day in 24 hour time.

$$\delta = 23.45\sin\left(360\left(\frac{284+n}{365}\right)\right) \quad (2.3)$$

$$\omega = 15(12 - H_r) \quad (2.4)$$

The diffuse radiation, I_d, is that portion of solar radiation that is scattered downwards by the molecules in the atmosphere. During clear days, the magnitude of I_d is about

10 to 14% of the solar radiation received at the earth's surface. I_d can be estimated as direct radiation incident at 60^o on the collector surface by equation (2.5) (Sukhatme, 2003; Bennamoun and Belhamri, 2003), where C is the diffuse radiation factor.

$$I_d = CI_b \cos 60^0 = 0.5CI_b \quad (2.5)$$

The total solar radiation, I_t, incident on the horizontal surface such as the collector plate of a solar dryer is therefore obtained by adding the direct and diffuse components of solar radiation as shown in equation (2.6). The total solar radiation is of great importance for solar dryers since it captures the required components of solar energy that is harnessed in the dryer.

$$I_t = I_b(1+0.5C) \quad (2.6)$$

The total solar radiation harnessed by the dryer provides the heat energy incident on the collector surface, Q_i, which is necessary for the drying process. This heat energy is expressed in equation (2.7), where A is the area of the energy collector (m^2) and τ is the transmissivity of the collector material.

$$Q_i = I_t A\tau \quad (2.7)$$

2.2 Model for Heat Transfer

A schematic solar tent dryer showing the energy balance on and within the dryer is shown in Figure 2.2. The amount of solar radiation entering the dryer is dependent on the magnitudes of incident, direct and diffuse solar irradiances, the angles of incidence between the solar beams and the dryer roof and walls, and the solar transmittance, reflectance and absorbance of the cover material (Ajwang, 2005; Sukhatme, 2003).

The analysis of the energy harnessed by the dryer is based on several assumptions. The first assumption is that there is no heat gain or loss from the collector surface except heat loss that can be evaluated from the overall heat loss coefficient. Next, energy harnessed is evaluated under steady state conditions, in which the drying material has stabilized in temperature gain or loss. Further, the dryer and drying plate walls are adiabatic and of negligible heat capacities. Furthermore, the heat radiated by the inner walls of the dryer and the plates is negligible. Finally, temperature gradient within an individual particle of the drying material is negligible.

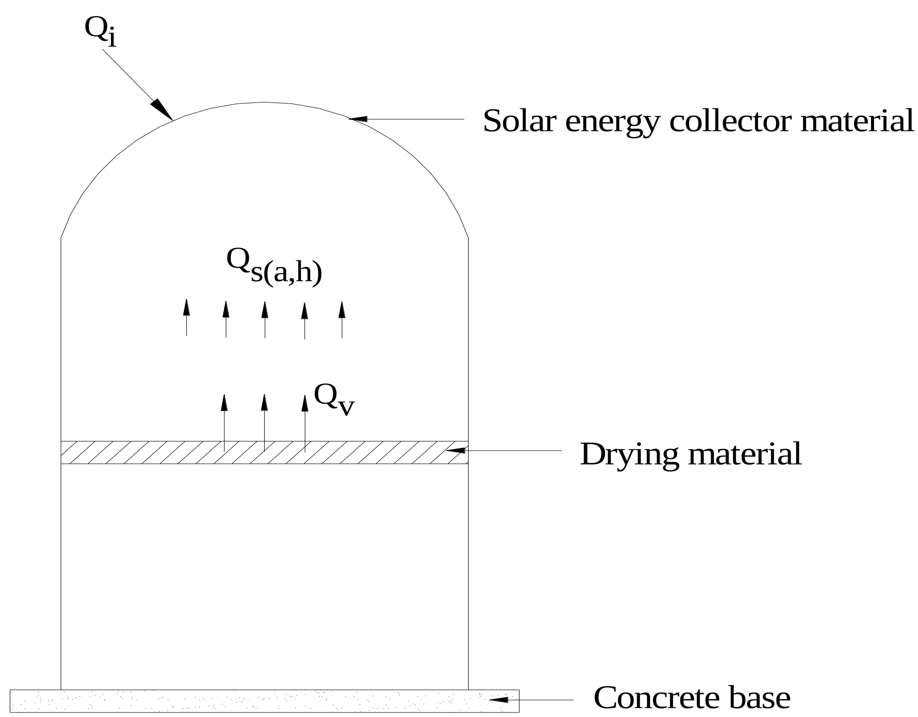

Figure 2.2 Schematic of the solar tent dryer showing components of energy balance.

Based on the above assumptions, the heat balance for the sinks and sources of energy in a solar tent dryer is given by equation (2.8). In this equation, Q_a is the useful energy absorbed by the drying air and the material being dried, and Q_L is the energy losses (Sukhatme, 2003; Al-Ajlan *et al.*, 2003). The energy component Q_a comprises the sensible heat of the air and humidity inside the dryer, $Q_{s(a,h)}$, and the heat of vapourization of moisture from the drying material, Q_v, given by equations (2.9) and (2.10), respectively. In these equations, m_a is the air mass flow rate (kg/s), ΔT is the temperature difference (K), C_{pa} is the specific heat capacity of air (J/kg-K), H is the humidity ratio of air (kg water/ kg dry air), C_{pw} is the specific heat capacity of water vapour (J/kg-K), h_{fg} is the latent heat of vapourization and $\partial M/\partial t$ is the drying rate of the material.

$$Q_a = Q_i - Q_L \tag{2.8}$$

$$Q_{s(a,h)} = m_a \Delta T (C_{pa} + HC_{pw}) \tag{2.9}$$

$$Q_v = h_{fg} \partial M/\partial t \tag{2.10}$$

To account for heat losses, Q_L is computed based on the overall energy loss coefficient U (W/m^2-K) and is given by equation (2.11) (Sukhatme, 2003). Equations (2.8)–(2.11) can be simplified to obtain equation (2.12) which relates the harnessed solar energy to the heat transfer mechanism in the solar tent dryer.

$$Q_L = UA\Delta T \tag{2.11}$$

$$I_t = \frac{\Delta T}{\tau}\left[\frac{m_a}{A}(C_{pa} + HC_{pw}) + U\right] + h_{fg} \partial M/\partial t \tag{2.12}$$

2.3 Model for Moisture Transfer under Thin Layer Drying

The theoretical equations of moisture transfer in grains are transient in nature and their solutions are not easy. Several approaches, including separating the moisture transfer equations for moisture movement in and around the grain, have been suggested. The equation for thin layer drying of grains is given by equation (2.13) as reported by

Brooker *et al*. (1992). In this equation, M is the moisture content (% d.b) at drying time *t* (hours), M_e is the equilibrium moisture content (% d.b), *k* is the drying rate constant (h^{-1}) and M = M_o (initial moisture content, % d.b) at *t*=0. Integration of equation (2.13) with constant of integration equal to unity yields equation (2.14) (Lahsasni *et al*., 2004).

$$\frac{\partial M}{\partial t} = k\,(M - M_e) \tag{2.13}$$

$$\frac{M - M_e}{M_o - M_e} = e^{-kt} \quad \text{(for } t > 0\text{)} \tag{2.14}$$

The ratio on the left hand side of equation (2.14) is referred to as moisture ratio (MR). During solar drying, the values of M_e are relatively small compared to M and M_o. In addition, the relative humidity of the drying air varies continuously. Therefore, equation (2.14) can be simplified to equation (2.15) (Yaldiz and Ertekin, 2001).

$$MR = \frac{M}{M_o} = e^{-kt} \tag{2.15}$$

Another important parameter that should be considered during drying is diffusivity which is used to indicate the flow of moisture out of the material being dried (Vizcarra-Mendoza *et al*., 2003). In the falling rate period of drying, moisture is transferred mainly by molecular diffusion. Moisture diffusivity is influenced mainly by moisture content and temperature of the material. For a drying process in which the absence of a constant rate is observed, the drying rate is limited by the diffusion of moisture from the inside to the surface layer, represented by Fick's law of diffusion (Crank, 1975). Assuming that amaranth grains can be approximated to spheres, the diffusion is expressed by equation (2.16) (Konishi *et al*., 2001), where D_e is the effective moisture diffusivity (m^2s^{-1}) and r_a is the radius (m) of amaranth grain.

$$\frac{\partial M}{\partial t} = D_e \left(\frac{\partial^2 M}{\partial {r_a}^2} \right) \tag{2.16}$$

For the transient diffusion in a sphere, assuming uniform initial moisture content and a constant effective diffusivity throughout the sample, the analytical solution of equation (2.16) yields equation (2.17).

$$MR = \frac{M - M_e}{M_o - M_e} = \left(\frac{6}{\pi^2} \right) \exp\left[-D_e t \left(\frac{\pi^2}{{r_a}^2} \right) \right] \tag{2.17}$$

The effective moisture diffusivity is determined by applying logarithms to equation (2.17) to obtain a linear relation of the form shown in equation (2.18). Therefore, a plot of ln(MR) versus time yields a straight line, and the diffusivity is determined from the slope (slope = $-D_e\pi^2/{r_a}^2$).

$$\ln(MR) = \ln\left(\frac{6}{\pi^2} \right) - \left(D_e \frac{\pi^2}{{r_a}^2} \right) t \tag{2.18}$$

CHAPTER THREE

3. MATERIALS AND METHODS

3.1 Amaranth Grain Sample Preparation

Amaranth seeds were planted at the Horticultural farm of Jomo Kenyatta University of Agriculture and Technology (JKUAT) in order to obtain freshly harvested grains for the study. JKUAT is located in Juja (37.05^{o} E longitude, 1.19^{o} S latitude and at an altitude of 1550 m above sea level). The mean annual temperature of Juja is 18.9^{o}C with mean annual maximum and minimum temperatures of 26.1 and 13.6^{o}C, respectively. The relative humidity ranges from 15 to 80% (Muchena *et al*., 1978).

Amaranth (*Amaranthus cruentus*) seeds were planted during the month of October 2008 in a plot measuring 6 m × 3 m and in rows spaced at 0.5 m. The seeds were planted in holes spaced at 0.2 m within a row in finely prepared loam soil which was packed to assure good seed-to-soil contact. The rains were not adequate during this period and irrigation was therefore necessary to ensure good germination. Germination took three to four days and the weeding between rows was done after two weeks from germination. The plants were thinned after three weeks of germination in order to leave three plants per hole. This was followed by another thinning after two more weeks which left one plant per hole in order to provide sufficient air and sunlight to the crop (Prim, 2003). The amaranth plants at different growth stages from the planting date are shown in Appendix Plates C1–C4. Fresh amaranth grains were harvested from the plot with a moisture content of approximately 64% d.b after 90 days. The harvesting involved detaching grain samples from the seed heads of the plants and cleaning them manually to remove any foreign material before drying. Figure 3.1 shows a sample of the cleaned amaranth grains.

Figure 3.1 Plate showing cleaned amaranth grains.

3.2 Description of the Solar Tent Dryer

The schematic diagram of the natural convection solar tent dryer used in this study is shown in Figure 3.2. The dryer consisted of a chimney, the main structure, a door and a concrete base. The main structure measured 1.85 m wide, 2.73 m long and 2.55 m high. The top part of this structure was semi-circular in shape with a radius of 0.5 m and was entirely covered with a polyvinyl chloride (PVC) material. The dimensions of the door were 0.6 m wide and 1.8 m high. The PVC material is preferred because it filters radiations such as ultraviolet, which can destroy light sensitive nutrients in the material being dried (Leon *et al*., 2002).

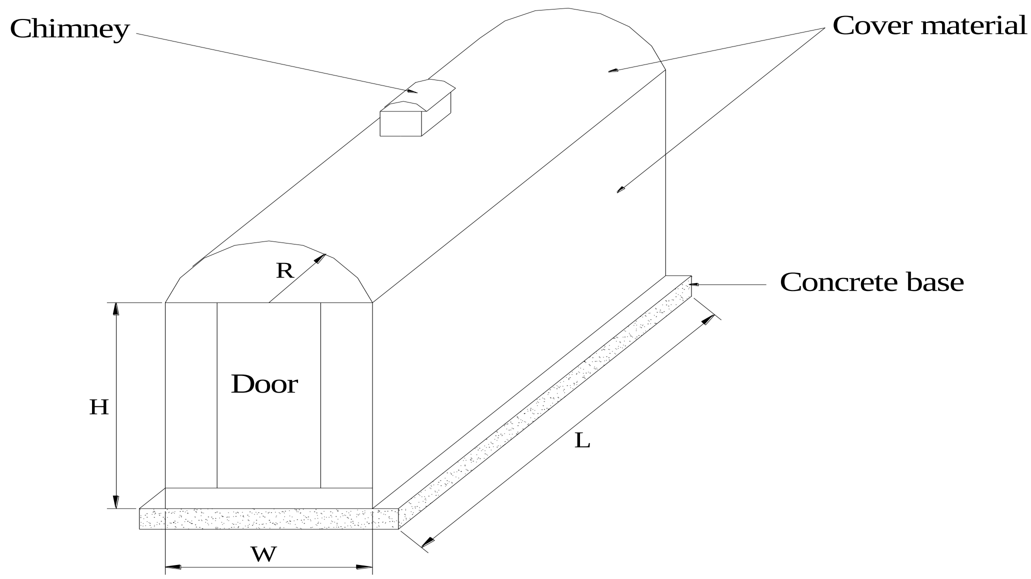

Figure 3.2 Schematic of the natural convection solar tent dryer. In this figure:

W = 1.85 m; L = 2.73 m; H = 2.05 m; R = 0.5 m.

Two layers of drying trays were used in the dryer, each layer measuring 0.5 m wide, 2.45 m long and 0.75 m high as shown in Figure 3.3. Layer 1 was raised 0.75 m above the concrete surface while Layer 2 was at a height of 1.5 m. Flat and angled iron bars were used to fabricate these trays, and a fine wire mesh placed at the top of each layer on which the drying material were placed. The chimney measuring 0.2 m long, 0.2 m wide and 0.4 m high was provided at the top center of the dryer to enhance natural convective air circulation. The solar tent dryer was placed on a concrete base measuring 1.95 m wide, 2.83 m long and 0.075 m high. The concrete base was provided in order to collect grains easily in case of spillage, to concentrate heat harnessed in the dryer, and to avoid water draining into the dryer.

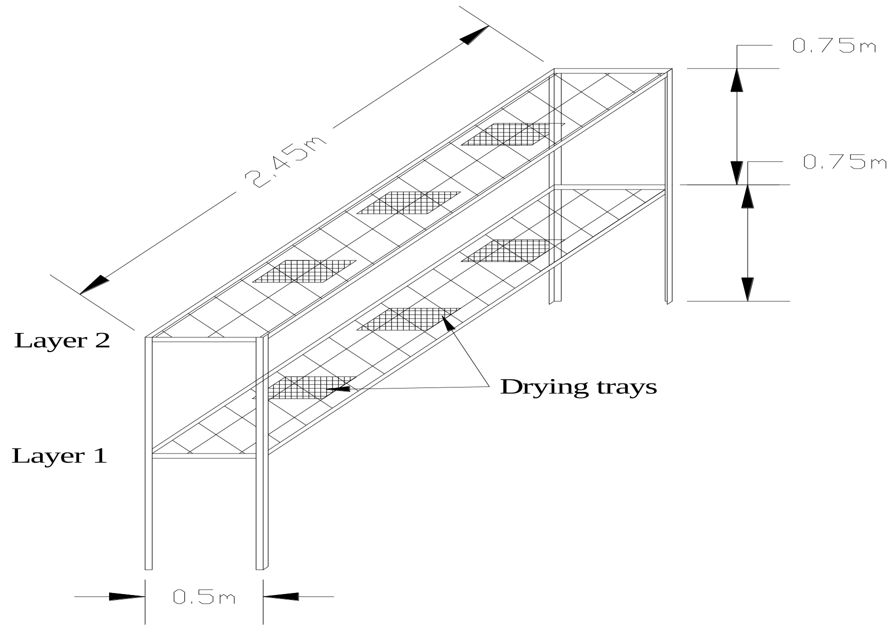

Figure 3.3 Schematic diagram showing the arrangement of drying trays in two layers.

3.3 Analyzing the Distribution of Temperature in the Solar Tent Dryer

Traditionally, grains are dried in solar dryers in single layers (Basunia and Abe, 2001). The need for enhancing output and efficiency, and for minimizing cost requires that grains be dried in a series of layers. To determine the suitable positions of these layers, it is necessary that the temperature distribution in the solar tent dryer be evaluated. In this study, the evaluation was carried out by monitoring temperatures at different locations in the x,y,z-plane in the dryer, the origin being the centre of the ground surface inside the dryer. The positions for recording temperature distribution were defined by discrete points (x_i,y_j,z_i) as shown in Figure 3.4, on which m_1 vertical lines, n_1 lateral lines and p_1 horizontal lines were distributed. The discrete points were located at intersections of the lines and the coordinates were established from equations (3.1)–(3.3). In these equations, W, L and H are the width, length and height of the main structure (Figure 3.2), respectively.

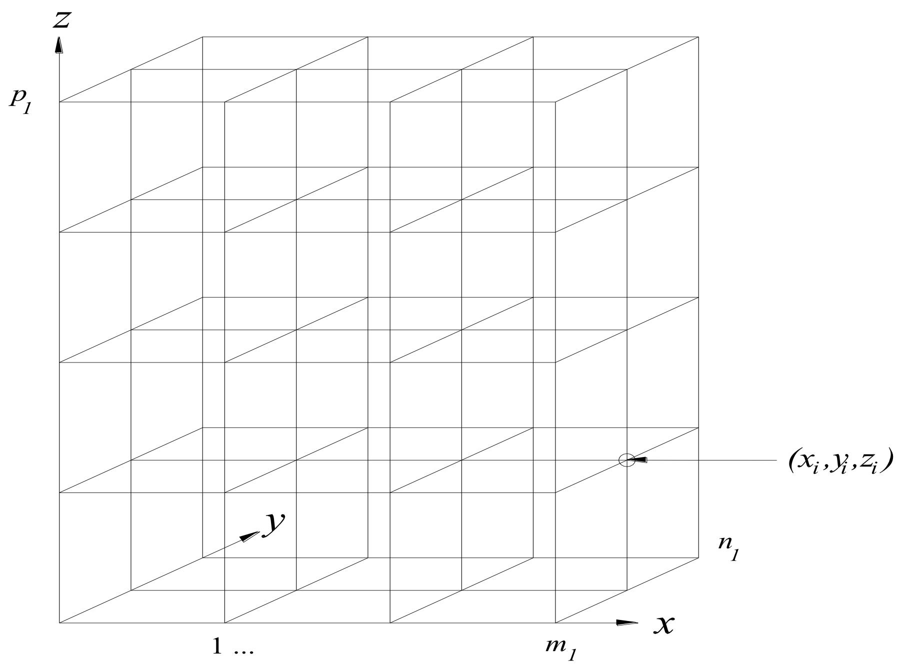

Figure 3.4 Discretization of temperature distribution points in the solar tent dryer.

$$x_i = (i-1)\,\frac{\mathrm{W}}{(m_1-1)}\Big|_{i=1\ to\ m_1} \tag{3.1}$$

$$y_i = (j-1)\,\frac{\mathrm{L}}{(n_1-1)}\Big|_{j=1\ to\ n_1} \tag{3.2}$$

$$z_i = (l-1)\,\frac{\mathrm{H}}{(p_1-1)}\Big|_{l=1\ to\ p_1} \tag{3.3}$$

Figure 3.5(b) shows two planes (Planes 1 and 2) in the solar tent dryer on which nine discrete points on each plane (Figure 3.5(a)) were located for monitoring temperature distribution. These points were defined in such a way that the Plane 1 was considered to be in the positive *x*-direction and at a vertical distance of 0.75 m from the ground surface (z = 0.75 m). Plane 2 was set at 0.75 m higher from the lower plane (z = 1.5 m) to avoid shading and enhance air circulation. The spacing between the concrete surface and Plane 1, and between Planes 1 and 2 of 0.75 m was subjectively set. The points along the two planes constituted the *y* coordinates.

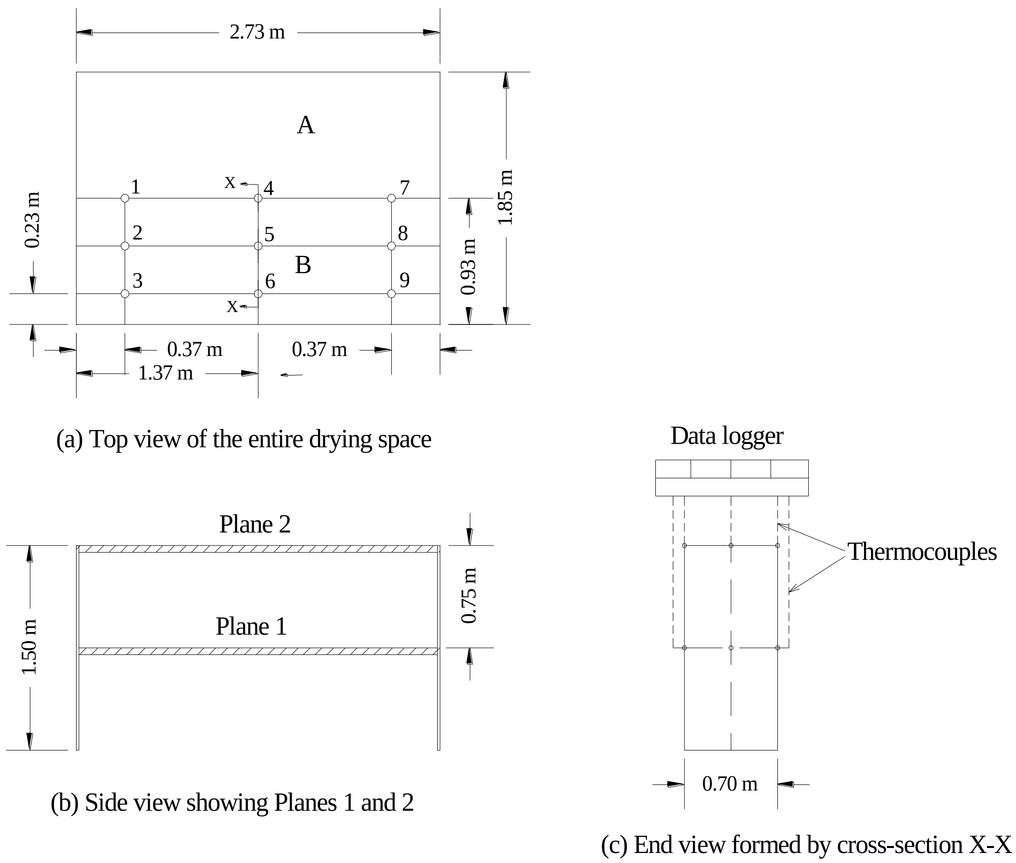

Figure 3.5 Schematic of temperature distribution acquisition system in the solar tent dryer.

The temperatures were monitored using thermocouples which relayed the information from the discrete points to a Thermodac electronic data logger (ETO Denki E, Japan) with ±1^{o}C accuracy (Figure 3.5(c)). The data were acquired for three consecutive days for 10 hours on each day at intervals of one hour starting from 8:00 a.m. Preliminary tests conducted on temperature distribution in Sections A and B (see Figure 3.5(a)) established that the temperatures in the two sections were not significantly different

(Appendix Table A1). Hence, in this study temperatures were monitored only in Section B of the solar tent dryer. A total of 90 daily temperature data (Appendix Tables A2–A4) were obtained for each plane for three consecutive days. Analysis of variance (ANOVA) was conducted on the data using GenStat (Discovery Edition 3) statistical tool to determine whether or not there existed significant difference for temperature distribution within the same plane and between planes.

3.4 Determining the Effect of Colour of Cover Material on Thin Layer Drying of Amaranth Grains

In order to determine the effect of cover material transmissivity on thin layer drying of amaranth grains, model solar tent dryers (Appendix Plates C5 and C6) were used instead of the actual tent dryer. This was because model dryers were easy to construct and needed smaller sizes of PVC cover materials to seal the structure. The model solar tent dryers shown in Figure 3.6 were covered with clear, yellow and nectarine diffused PVC materials of 200 micron thickness whose transmissivities were 90, 85 and 82%, respectively (Amiran Kenya Limited). These models were obtained by scaling down the actual dryer by a factor of 0.2. Thermocouples were used to sense and relay temperature data from the model tent dryers to the data-logger while a digital thermo-hygrometer (HC-520, Hong Kong), with ±5% accuracy with a range of 20 to 99%, was used to obtain relative humidity values. Amaranth grain sample of approximately 50 g was evenly spread on a drying tray (0.25 m × 0.25 m) to form a single layer. The control involved drying the grains in the open sun.

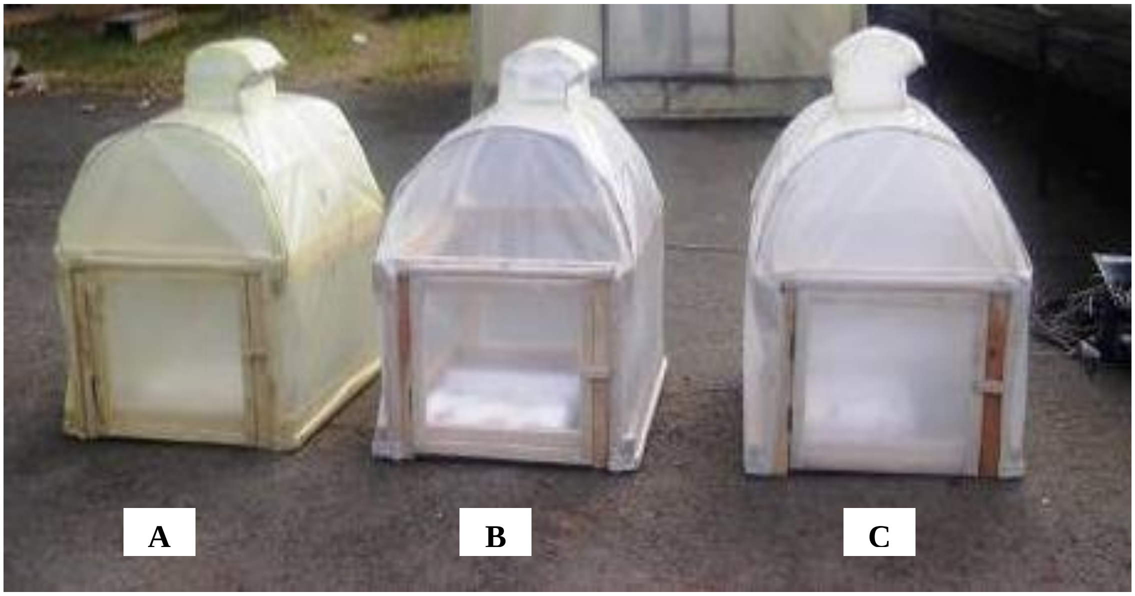

Figure 3.6 Plates showing the experimental set-up of the model solar tent dryers. In the figure: A, yellow cover; B, clear cover; C, nectarine diffused cover.

Data acquisition involved recording temperature and relative humidity values in the open sun and inside the model dryers. The moisture content of the grains during drying was also monitored. The data were recorded at 30 minutes intervals from 8:00 a.m to 5:00 p.m for three consecutive days (Appendix Tables A5 and A6). In order to determine the moisture content, grain samples were weighed in a drying dish of known weight and the wet weight recorded as W_t. The capacity and sensitivity of Shimadzu electronic balance (LIBROR EB-4300D, Japan) used were 600g and 0.01g, respectively. The samples were placed in a constant-temperature oven set at a temperature of 105^{o}C for about 24 hours. The dried grains were removed from the oven and the dry weight, W_d, recorded. The percent dry basis moisture content, M, was then evaluated from the expression (Bala, 1997) given by equation (3.4).

$$M = \frac{W_t - W_d}{W_d} * 100 \qquad (3.4)$$

The data collected were used to plot graphs relating temperature, relative humidity and moisture content with drying time for the different cover materials in order to compare the performance of the different materials with the open sun. An ANOVA was also conducted to determine whether there existed significant differences within the performance of the different cover materials, and between the materials and the open sun.

3.5 Modeling Thin Layer Solar Drying of Amaranth Grains

3.5.1 Determining Moisture Ratio and Effective Moisture Diffusivity of Amaranth Grains

The modeling of thin layer drying of amaranth grains required the determination of moisture ratio and effective moisture diffusivity. The dimensionless moisture ratio (MR) as computed using equation (2.15) was based on the theory of thin layer drying (Kingsly *et al.*, 2007; Uluko *et al.*, 2006). The parameters that characterize size, shape and mass of the particle such as the effective diameter, sphericity and specific weight are fundamental to modeling of drying operations. The physical parameters of amaranth grains that were used in the computation of the effective moisture diffusivity are presented in Table 3.1.

Table 3.1 Physical parameters of amaranth grains

Average diameter (d_{av}), m	Sphericity (Φ_s)	True density (ρ_p), kg/m^3	Bulk density (ρ_e), kg/m^3
0.001	1	1370	860

(Source: Vizcarra-Mendoza *et al.*, 2003)

3.5.2 Data Acquisition

The data used for determination of moisture ratio and effective moisture diffusivity for the model dryers has already been reported in Section 3.4. However, the acquisition of data for thin layer drying in the actual solar tent dryer required even spreading of 50 g sample of grains on two similar square drying trays of sides 0.25 m. The trays were placed in the dryer on Layers 1 and 2 as shown in Figure 3.3. The positioning of the trays on the planes was such that the centres of the lower and upper trays coincided with nodes of coordinates (0.19W, 0.00L, 0.37H) and (0.19W, 0.00L, 0.74H), respectively. Ambient temperature and relative humidity, and temperature and relative humidity inside the dryer, and the moisture content of the grains were monitored and recorded. They were recorded at 30 minutes intervals from 9:00 a.m to 5:00 p.m for three consecutive days. The tests for the actual dryer (Appendix Plate C7) were conducted two days after those for the model dryers. Temperature, relative humidity and moisture content data were recorded at intervals of 30 minutes from 9:00 a.m to 4:00 p.m using the same equipment described in Section 3.3. The control involved drying the grains in the open sun. Due to unavailability of equipment to measure the actual solar energy, solar radiation data was evaluated from electronic world satellite solar maps (Mohandes *et al.*, 2000) in order to relate it to the recorded temperature and relative humidity during the period of study.

3.5.3 Data Analysis

In order to model the thin layer drying amaranth grains for dryers with different cover materials, the actual solar tent dryer and the open sun, initially the data acquired were utilized to plot graphs that related temperature, relative humidity and moisture content with drying time. The graphs were used in the analysis of the effect of drying conditions on drying amaranth grains. Thereafter, the thin layer drying equations presented in Table 2.1 were evaluated so as to select the best model for describing the drying rate of amaranth grains under natural convection solar drying. Modeling the drying behaviour of different agricultural products often requires use of statistical tools (Kassem, 1998; O'Callaghan *et al.*, 1971; Werma *et al.*, 1985). In this study, regression analysis was conducted on the moisture data using GenStat in order to compare the performance of the models in predicting the drying rate of amaranth grains. The comparison involved determining coefficient of determination (R^2), reduced chi-square (χ^2) and root mean square error (RMSE). The higher the values of R^2, and the lower the values of χ^2 and RMSE, the better the goodness of fit (Yaldiz and Ertekin, 2001; Sacilik and Elicin, 2006). The χ^2 and RMSE were computed using equations (3.5) and (3.6), where $MR_{act,i}$ and $MR_{pre,i}$ are the actual and predicted moisture ratios, respectively, N and n_c are the number of observations and constants found in the respective model, respectively (Doymaz *et al.*, 2004; Sarsavadia *et al.*, 1999).

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{act,i} - MR_{pre,i}\right)^2}{N - n_c} \tag{3.5}$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{act,i}\right)^2\right]^{1/2} \tag{3.6}$$

The prediction performances (η_p) of the models were also compared. These were determined by equation (3.7), where N_c and N_t represent the number of correctly predicted and trial data, respectively (Uluko *et al.*, 2006). The performances were based on residual error intervals of ±5 and ±10%. The absolute residual error (ε) was defined as shown in equation (3.8) (Kanali, 1997).

$$\eta_p\ (\%) = 100 \times \frac{N_c}{N_t} \tag{3.7}$$

$$\varepsilon\ (\%) = \left| \frac{(MR_{prei} - MR_{acti})}{MR_{acti}} \times 100 \right| \tag{3.8}$$

3.6 Determining the Effect of Colour of Cover Material on Physical, Optical and Nutritive Properties of Amaranth Grains

Amaranth grains dried under different cover materials and in the open sun were sampled and their properties (viz., physical, optical and nutritive) determined. Hardness, which is important during milling process of amaranth, was selected to represent the physical property while colour and crude protein content represented the optical and nutritive properties, respectively.

3.6.1 Hardness as a Physical Property

The hardness of dried amaranth grains was determined using the hardness tester (Kiya Seisakusho Ltd, Tokyo, Japan) with a capacity of 20 kg. The test involved holding the grain sample between the two faces of the tester while increasing the force until the grain crushed. Hardness values were recorded at the crushing point. The tests were done in six replicas to achieve accurate and reliable results.

3.6.2 Colour as an Optical Property

For colour tests, dried amaranth grains (approximately 10 g) were placed into a clear polythene paper which was subjected to a spectrophotometer (NF333, Nippon

Denshoku, Japan). The sensor of the meter was pointed directly at the grains to record the colour values while care was taken to avoid any interference from ambient light sources. The tests were conducted in a clean and air-conditioned room to avoid any deposits on the instrumental components. The colour of the grains was measured, in six replicas, for *L** (light-dark spectrum), *a** (green-red spectrum) and *b** (blue-yellow spectrum) values. The parameters *L**, *a** and *b** range from 0 (black) to 100 (white), -60 (green) to +60 (red), and -60 (blue) to +60 (yellow), respectively. Hue angles (*h**) were calculated using equation (3.9) (McGuire, 1992).

$$h* = \tan^{-1}\left(\frac{b*}{a*}\right) \quad (3.9)$$

3.6.3 Crude Protein Content as a Nutritive Property

The Kjeldahl method of nitrogen analysis is the worldwide standard for calculating the protein content in a wide variety of materials (Blamire, 2003). It consisted of three steps, which were carefully carried out in sequence. In the first step, the sample was digested in strong sulphuric acid in the presence of a catalyst, which helped in the conversion of the amine nitrogen to ammonium ions. Next, the ammonium ions were then converted into ammonia gas, heated and distilled. The ammonia gas was directed into a trapping solution where it dissolved and became an ammonium ion once again. Finally, the amount of the ammonia that had been trapped was determined by titration with a standard solution, and the percentage nitrogen (%N) and crude protein (CP) were obtained from equations (3.10) and (3.11). In these equations, V_1 is titre for sample (ml), V_2 is titre for blank (ml), N_s is normality of standard hydrochloric acid (HCL) solution (0.02), f is factor of standard HCL solution (approximately 1), V is volume of diluted digest taken for distillation (10 ml), S is weight of sample taken (1 g) and PF is the protein factor which is approximately 6.25.

$$\%N = (V_1 - V_2) \times N_s \times f \times 0.014 \times \frac{100}{V} \times \frac{100}{S} \quad (3.10)$$

$$CP = \%N \times PF \quad (3.11)$$

CHAPTER FOUR

4. RESULTS AND DISCUSSIONS

4.1 Analysis of Temperature Distribution in the Solar Tent Dryer

The distribution of mean temperatures for Planes 1 and 2 are shown in Tables 4.1 and 4.2, respectively. The mean temperatures and standard deviations for Plane 1 ranged from 38.2–38.4^{o}C and 6.8–7.3^{o}C, respectively. The corresponding values for Plane 2 ranged from 38.8–39.2^{o}C and 6.6–6.9^{o}C, respectively. This shows that the temperature distribution within the planes were of the same magnitude. However, the temperatures for Plane 2 were slightly higher than those of Plane 1. This is because Plane 2 was closer to the solar energy collector surface.

An analysis of variance for temperature distribution within each plane and between the planes yielded the results shown in Tables 4.3–4.5. The results in Table 4.3 (p-value, 0.999; $F_{critical}$, 2.055; $F_{computed}$, 0.002) and in Table 4.4 (p-value, 0.999; $F_{critical}$, 2.055; $F_{computed}$, 0.007) show that there was no significant difference in temperature distribution within the planes as the $F_{computed}$ values were lower than the $F_{critical}$ at 5% level of significance.

Table 4.1 Distribution of mean temperatures in the solar tent dryer for Plane 1

Time (hours)	**Discrete points at which temperatures were monitored**									**Mean±Stdev**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	
1	27.8	28.1	28.5	28.4	28.2	29.1	28.6	28.3	28.5	28.4±0.4
2	29.0	29.2	29.5	29.0	29.4	29.6	29.3	29.8	29.8	29.4±0.3
3	30.7	31.2	30.8	31.0	31.2	31.3	31.0	31.2	31.0	31.0±0.2
4	32.6	32.5	32.4	33.1	32.8	32.9	33.1	32.8	32.6	32.2±0.2
5	41.0	41.4	41.5	40.8	41.7	41.2	41.2	41.5	41.5	41.3±0.3
6	46.1	46.2	46.1	45.8	46.6	46.2	46.0	46.3	46.2	46.2±0.2
7	46.0	46.2	45.9	45.8	46.2	45.7	45.5	45.8	46.0	45.9±0.2
8	44.5	44.9	44.6	44.0	44.3	43.8	43.5	44.0	44.3	44.2±0.4
9	42.8	43.0	42.6	42.7	42.8	42.5	42.3	42.8	42.7	42.2±0.2
10	41.2	41.0	41.3	41.6	41.2	41.1	41.4	41.1	41.0	41.2±0.2
Mean	38.2	38.4	38.3	38.2	38.4	38.3	38.2	38.4	38.3	
Stdev	7.3	7.3	7.2	7.0	7.2	6.8	6.9	7.0	7.1	

Plane 1 is located at 0.75 m above the concrete surface

Table 4.2 Distribution of mean temperatures in the solar tent dryer for Plane 2

Time (hours)	**Discrete points at which temperatures were monitored**									**Mean±Stdev**
	10	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	
1	29.2	29.3	29.1	29.4	29.4	29.1	29.1	29.5	29.2	29.2±0.2
2	30.6	30.9	30.1	30.6	30.5	30.7	30.2	30.6	30.4	30.5±0.2
3	31.7	32.1	31.3	32.1	31.2	32.0	31.4	32.2	31.8	31.8±0.4
4	34.2	34.6	34.5	34.9	34.4	35.0	34.7	35.2	34.1	34.6±0.4
5	42.2	42.0	42.0	42.9	41.8	42.6	42.0	42.7	41.8	42.2±0.4
6	46.3	46.1	46.0	46.3	45.8	46.1	46.0	46.1	45.8	46.1±0.2
7	46.5	46.3	46.0	46.1	46.1	46.1	45.6	45.9	45.7	46.0±0.3
8	45.2	45.1	44.8	45.0	45.0	45.1	45.0	45.1	44.7	45.0±0.2
9	43.5	43.3	43.3	43.6	43.3	43.4	43.2	43.4	43.4	43.4±0.1
10	42.1	41.9	41.3	41.4	41.6	42.0	41.7	41.6	41.6	41.7±0.3
Mean	39.1	39.2	38.8	39.2	38.9	39.2	38.9	39.2	38.8	
Stdev	6.9	6.7	6.8	6.7	6.8	6.8	6.8	6.6	6.7	

Plane 2 is located at 1.5 m above the concrete surface

Table 4.3 ANOVA corresponding to temperature distribution within Plane 1

Source of Variation	*s.s.*	*d.f.*	*m.s.*	$F_{computed}$	*p-value*	$F_{critical}$
Discrete points	0.7	8	0.1	0.002	0.999	2.055
Residual	4077.0	81	50.3			
Total	4077.7	89				

Table 4.4 ANOVA results corresponding to temperature distribution within Plane 2

Source of Variation	*s.s.*	*d.f.*	*m.s.*	$F_{computed}$	*p-value*	$F_{critical}$
Discrete points	2.5	8	0.3	0.007	0.999	2.055
Residual	3699.7	81	45.7			
Total	3702.2	89				

Table 4.5 ANOVA results corresponding to temperatures between Planes 1 and 2

Source of Variation	*s.s.*	*d.f.*	*m.s.*	$F_{computed}$	*p-value*	$F_{critical}$
Planes	2.8	1	2.8	0.058	0.813	4.414
Residual	863.1	18	47.9			
Total	865.9	19				

Similarly, the results in Table 4.5 show that there was no significant difference in temperature distribution between the planes as the $F_{computed}$ was less than the $F_{critical}$ (*p*-value, 0.813; $F_{critical}$, 4.414; $F_{computed}$, 0.058). These results are in agreement with the observations reported by Mwithiga and Kigo (2006) in studying the temperature distribution in a solar dryer with limited sun tracking capability. The above findings imply that one can achieve uniform drying of agricultural produce when drying in thin layers on any plane in the solar tent dryer. Further, the results demonstrate that the dryer output can be doubled at minimal cost by drying the produce on two vertical layers in the solar tent dryer without compromising on the drying efficiency. However, when drying on different layers shading should be avoided and the spacing between the planes should be such that air circulation is not inhibited.

4.2 Effect of Colour of Cover Material on Thin Layer Drying of Amaranth Grains under Model Solar Tent Dryers

The temperatures developed under the different cover materials and the open sun is shown in Figure 4.1. The results indicate that the temperatures developed in the dryer with the nectarine diffused cover material were consistently lower (41.4±5.3^{o}C) than those dryers with the yellow (42.3±5.8^{o}C) and clear (44.5±5.8^{o}C) cover materials. In addition, the temperatures developed by the clear cover material were consistently the highest. At any given time the temperature difference between the three cover materials were not significant. The clear cover material developed the highest temperatures since it allowed more heat radiation to penetrate due to its higher transmissivity (τ = 90%) (Charles *et al*., 2005). The figure also shows that the temperatures recorded in the open sun were significantly lower than those recorded in the dryers with different cover materials.

An ANOVA at 5% level of significance on the data (Table 4.6) confirmed that there were no significant differences between the temperatures developed by the different cover materials (p-value, 0.257; $F_{critical}$, 3.191; $F_{computed}$, 1.398). However, the results in Table 4.7 show that there was significant difference ($p<0.05$) between the temperatures in the open sun and those developed in the dryers with different cover materials.

Similar variations of temperature in a natural convection solar dryer and the open sun have been reported previously (Basunia and Abe, 2001).

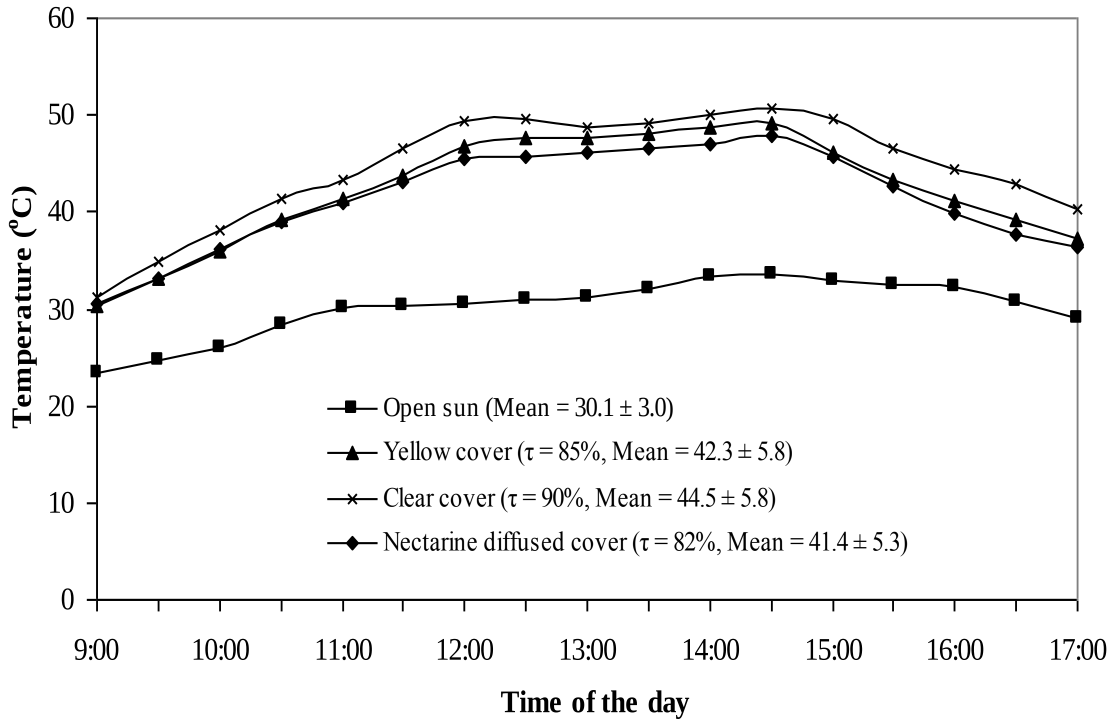

Figure 4.1 Temperatures in dryers with different cover materials and the open sun.

Table 4.6 ANOVA results corresponding to temperatures developed in the dryers with different cover materials

Source of Variation	*s.s.*	*d.f.*	*m.s.*	$F_{computed}$	*p-value*	$F_{critical}$
Dryers	87.9	2	44.0	1.398	0.257	3.191
Residual	1508.6	48	31.4			
Total	1596.5	50				

Table 4.7 ANOVA results corresponding to temperatures in the open sun and those in the dryers with different cover materials

Source of Variation	*s.s.*	*d.f.*	*m.s.*	$F_{computed}$	*p-value*	$F_{critical}$
Drying condition	2113.4	3	704.5	27.320	1.71×10^{-11}	2.748
Residual	1650.2	64	25.8			
Total	3763.6	67				

The relative humidity values in dryers covered with different materials and the open sun are shown in Figure 4.2. It is observed from the figure that relative humidity values in the open sun were always higher (28.9±6.2%) than those in covered dryers. The relative humidity values at any given time were not significantly different under both conditions. At any given time, there was a decreasing trend in relative humidity for all dryers. When Figures 4.1 and 4.2 are considered, it is noted that at any given time the temperatures increased from the open sun, nectarine diffused, yellow to clear cover materials with a concomitant decrease in relative humidity. This indirect relationship has also been reported by Basunia and Abe (2001).

At 5% level of significance, ANOVA (Table 4.8) on the relative humidity values in the open sun and in the covered dryers showed no significant difference (*p*-value, 0.090; $F_{critical}$, 2.748; $F_{computed}$, 2.263). Similarly, there was no significant difference (*p*-value, 0.839; $F_{critical}$, 2.748; $F_{computed}$, 0.282) in relative humidity when the different cover materials were compared (Table 4.9).

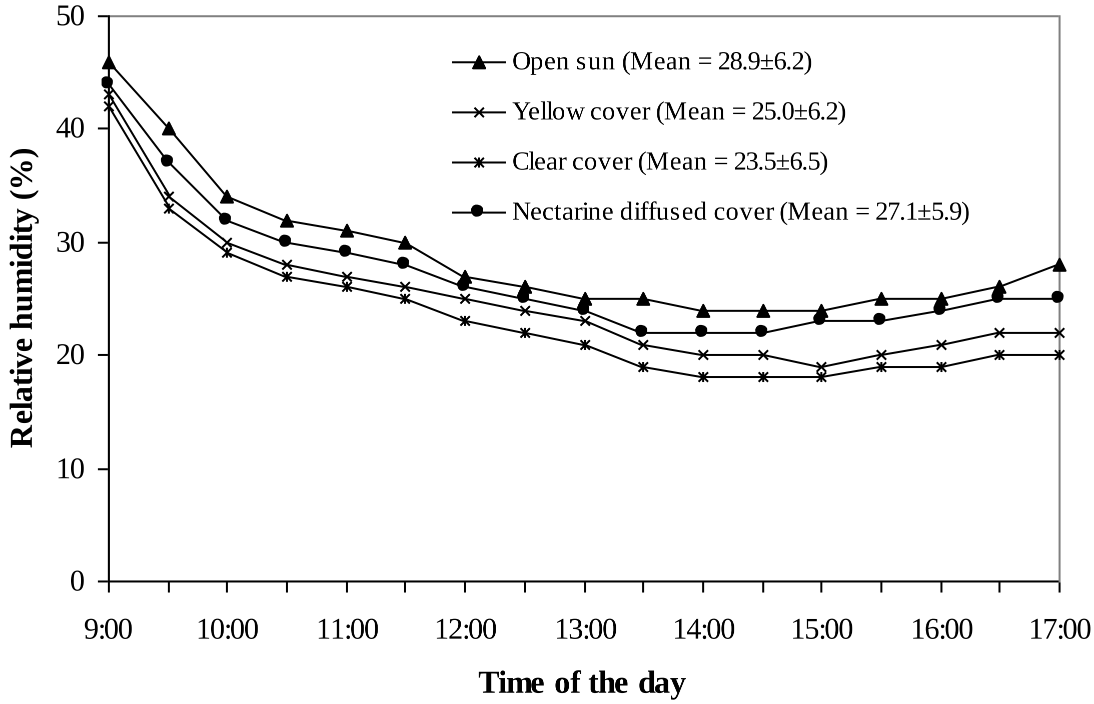

Figure 4.2 Relative humidity in dryers with different cover materials and the open sun.

Table 4.8 ANOVA results corresponding to relative humidity values recorded in the open sun and the dryers with different cover materials

Source of Variation	*s.s.*	*d.f.*	*m.s.*	$F_{computed}$	*p-value*	$F_{critical}$
Drying condition	277.0	3	92.3	2.263	0.090	2.748
Residual	2610.9	64	40.8			
Total	2887.9	67				

Table 4.9 ANOVA results corresponding to relative humidity values recorded in the dryers with different cover materials

Source of Variation	*s.s.*	*d.f.*	*m.s.*	$F_{computed}$	*p-value*	$F_{critical}$
Drying condition	265.7	3	88.6	0.282	0.839	2.748
Residual	20137.3	64	314.6			
Total	20403.0	67				

The drying curves of amaranth grains dried under dryers with different cover materials and in the open sun are presented in Figure 4.3. The individual drying curves for the dryers with different cover materials and the open sun are shown in Appendix Figure B1. The results show that under all the four drying conditions (viz., open sun, nectarine diffused cover, yellow cover and clear cover) the rate of drying was highest within the first 2.5 hours of drying. Thereafter, the drying rate reduced significantly. The moisture loss in amaranth grains decreased exponentially with increase in drying time. This behaviour is common with most cereal grains and confirms observations by Abalone *et al*. (2006) and Basunia and Abe (2001). Therefore, thin layer drying models shown in Table 1.1 can be applied to predict the drying behaviour of amaranth grains. As seen from the figure, there was no constant rate drying period and therefore the falling rate period prevailed in the entire thin layer drying process of amaranth grains. It is also worth noting that the grains dried from an initial moisture content ranging from 66.7–68.8% d.b to an equilibrium moisture content of 7% d.b. The equilibrium moisture content was obtained after 4.5, 6, 7 and 7.5 hours of drying for the clear cover, yellow cover, nectarine diffused cover and the open sun, respectively.

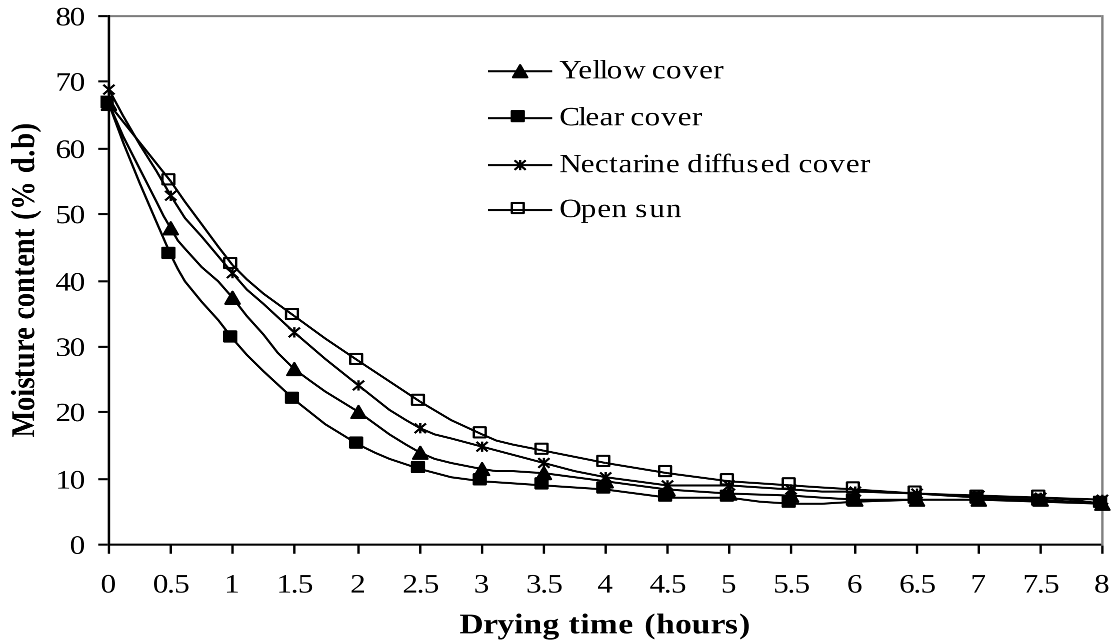

Figure 4.3 Drying curves for amaranth grains under dryers with different cover materials and the open sun.

The drying rate increased from open sun, through nectarine diffused cover, yellow cover to clear cover at any given time. However, the difference in drying rate was slight from the lowest to the highest. An ANOVA conducted at a 5% level of significance yielded the results shown in Table 4.10–4.12. From the results in Table 4.10, it is noted that for the first 2.5 hours of drying the drying rates were not significantly different under all the four drying conditions (*p*-value, 0.823; $F_{critical}$, 3.098; $F_{computed}$, 0.303). Further, Table 4.11 shows that the drying rates between 2.5–8 hours of drying were slightly different (*p*-value, 0.049; $F_{critical}$, 2.839; $F_{computed}$, 2.848). This can be explained by the difference in the energy and relative humidity levels required by the covered dryers and the open sun to attain the equilibrium moisture content.

General comparison, however, as presented in Table 4.12 showed that the drying rates for the entire drying period were not significantly different under all the four drying conditions (*p*-value, 0.839; $F_{critical}$, 2.748; $F_{computed}$, 0.282). Similar observations have been noted for most cereal grains and other agricultural products (Basunia and Abe, 2001; Sacilik *et al*., 2006). This implies that the solar dryer can dry products faster than the open sun.

Table 4.10 ANOVA results corresponding to moisture content of amaranth grains under the PVC covered dryers and in the open sun within the first 2.5 hours of drying

Source of Variation	*s.s.*	*d.f.*	*m.s.*	$F_{computed}$	*p-value*	$F_{critical}$
Drying condition	332.8	3	110.9	0.303	0.823	3.098
Residual	7321.7	20	366.1			
Total	7654.5	23				

Table 4.11 ANOVA results corresponding to moisture content of amaranth grains under the PVC covered dryers and in the open sun after 2.5 hours of drying

Source of Variation	*s.s.*	*d.f.*	*m.s.*	$F_{computed}$	*p-value*	$F_{critical}$
Drying condition	46.5	3	15.5	2.848	0.049	2.839
Residual	217.7	40	5.4			
Total	264.2	43				

Table 4.12 ANOVA results corresponding to moisture content of amaranth grains under the dryers with different cover materials and in the open sun

Source of Variation	*s.s.*	*d.f.*	*m.s.*	$F_{computed}$	*p-value*	$F_{critical}$
Drying condition	265.7	3	88.6	0.282	0.839	2.748
Residual	20137.3	64	314.6			
Total	20403.0	67				

In general, the temperatures attained in the dryers covered with PVC materials were higher than those in the open sun. It was also noted that the temperatures induced in the dryer with the clear PVC cover material were the highest. In addition, the relative humidity was lowest with the dryer with the clear cover material. Although the drying rates were not significantly different when drying under the four conditions (viz., open sun, nectarine diffused cover, yellow cover and clear cover), it took only 4.5 hours to attain the equilibrium moisture content for the dryer with the clear cover material as compared to 6–7.5 hours for the other three drying conditions. The prevailing trend of drying curves obtained imply that thin layer drying models can be applied to predict the drying behaviour of amaranth grains in the PVC covered dryers and the open sun. These findings demonstrate that natural convection solar tent dryers covered with PVC materials can be used to increase the drying rate of amaranth grains when dried in thin layers.

4.3 Modeling Thin Layer Solar Drying of Amaranth Grains

4.3.1 Model Evaluation in the Model Solar Tent Dryers and the Open Sun

The model coefficients and parameters of error analysis under the model solar tent dryers, and the open sun are presented in Tables 4.13–4.16. When all the six models are considered, the results show that the R^2 values obtained for the dryer covered with clear, yellow and nectarine diffused PVC materials, and the open sun ranged from 0.816–0.995, 0.917–0.996, 0.879–0.994 and 0.816–0.995, respectively. The corresponding values for the RMSE were 0.0195–0.1219, 0.0194–0.0853, 0.0240–0.1051 and 0.0195–0.1219, respectively. Those for the χ^2 were 0.0004–0.0172, 0.0004–0.0084, 0.0007–0.0127 and 0.0004–0.0172, respectively. Since high R^2, and low RMSE and χ^2 values were attained, the selected models satisfactorily predicted thin layer drying of amaranth grains.

Comparison of the six models (Tables 4.13–4.16) shows that the Page model attained the highest R^2 (0.994–0.999) and the lowest RMSE (0.0095–0.0240) and χ^2 (0.0001–0.0007) values. This observation illustrates that, even though all the tested models satisfactorily predicted the thin layer drying of amaranth grains, the Page model performed was the most appropriate.

Table 4.13 Estimated parameters and comparison criteria of moisture ratio for the model dryer with clear cover

Model	**Model coefficients and constants**	**R^2**	**RMSE**	**χ^2**	**ε (%)**	**η_p(%)**
Newton	k = 0.6533	0.941	0.0692	0.0051	22.1 ± 17.7	29.4
Page	k = 0.8235, n = 1.0872	0.995	0.0195	0.0004	3.3 ± 3.4	88.2
Modified Page	k = 0.8235, n = 1.0872	0.994	0.0218	0.0006	6.0 ± 3.7	82.4
Henderson & Pabis	a = 0.5893, k = 0.6533	0.816	0.1219	0.0172	11.0 ± 9.6	52.9
Logarithmic	a = 0.9427, k = 0.6533, c = -0.0348	0.975	0.0448	0.0025	18.0 ± 11.6	35.3
Wang & Singh	a = -0.3082, b = 0.0282	0.892	0.0936	0.0101	40.4 ± 28.3	11.8

Table 4.14 Estimated parameters and comparison criteria of moisture ratio for the model dryer with yellow cover

Model	**Model coefficients and constants**	**R^2**	**RMSE**	**χ^2**	**ε (%)**	**η_p(%)**
Newton	k = 0.6101	0.980	0.0425	0.0019	14.9 ± 11.6	41.2
Page	k = 0.7608, n = 0.9349	0.996	0.0194	0.0004	5.2 ± 5.1	88.2
Modified Page	k = 0.7608, n = 0.9349	0.995	0.0201	0.0005	4.3 ± 4.6	88.2
Henderson & Pabis	a = 0.7367, k = 0.6101	0.917	0.0853	0.0084	9.2 ± 6.8	70.6
Logarithmic	a = 0.9856, k = 0.6221, c = -0.0224	0.992	0.0266	0.0009	9.7 ± 7.9	58.8
Wang & Singh	a = -0.3137, b = 0.0278	0.935	0.0755	0.0066	31.2 ± 25.9	23.5

Table 4.15 Estimated parameters and comparison criteria of moisture ratio for the model dryer with nectarine diffused cover

Model	**Model coefficients and constants**	**R^2**	**RMSE**	**χ^2**	**ε (%)**	**η_p(%)**
Newton	k = 0.4909	0.961	0.0596	0.0038	31.5 ± 17.2	17.6
Page	k = 0.6630, n = 0.9176	0.994	0.0240	0.0007	10.6 ± 6.7	52.9
Modified Page	k = 0.6630, n = 0.9176	0.993	0.0260	0.0008	13.5 ± 7.5	29.4
Henderson & Pabis	a = 0.6937, k = 0.4909	0.879	0.1051	0.0127	20.8 ± 7.3	5.9
Logarithmic	a = 0.9936, k = 0.5052, c = -0.0365	0.988	0.0332	0.0014	12.3 ± 10.8	58.8
Wang & Singh	a = -0.3155, b = 0.0273	0.961	0.0599	0.0041	23.9 ± 24.3	29.4

Table 4.16 Estimated parameters and comparison criteria of moisture ratio for the open sun

Model	**Model coefficients and constants**	**R^2**	**RMSE**	**χ^2**	**ε (%)**	**η_p(%)**
Newton	k = 0.5742	0.994	0.0248	0.0007	12.3 ± 7.5	29.4
Page	k = 0.4900, n = 1.0806	0.999	0.0095	0.0001	3.3 ± 3.4	88.2
Modified Page	k = 0.4900, n = 1.0806	0.996	0.0199	0.0005	7.6 ± 5.7	64.7
Henderson & Pabis	a = 1.0727, k = 0.5742	0.996	0.0207	0.0005	11.1 ± 10.3	58.8
Logarithmic	a = 1.0343, k = 0.5742, c = 0.0061	0.997	0.0169	0.0003	9.3 ± 6.7	64.7
Wang & Singh	a = -0.3059, b = 0.0252	0.976	0.0479	0.0026	23.2 ± 32.9	47.1

Tables 4.13–4.16 further present the mean absolute residual errors and the corresponding standard deviations achieved by the six models. As seen from the tables, the Page model attained the lowest mean residual errors ranging from

3.3±3.4–10.6±6.7% when compared with the other models. The closer the value of mean absolute residual error is to zero, the better the prediction (Kanali, 1997). The computed absolute residual errors for moisture ratio under the different cover materials and the open sun (no cover) are presented in Appendix Tables A11–A14. On the other hand, the closer the value of the standard deviation of residual error is to zero, the more uniform prediction level is (Kanali, 1997). Therefore, the preceding results confirm that the Page model attained satisfactory prediction level for thin layer drying of amaranth grains as compared to other models. The prediction performances of the models are also shown in Tables 4.13–4.16. The prediction performance was based on a ±10% residual error interval. It is seen from the tables that the Page model attained the highest prediction performances of 88.2% for the dryers that were covered with clear and yellow PVC material, and the open sun further confirming the superiority of the Page model.

Comparison of the moisture ratios predicted by the Page model and the actual values for model solar tent dryer with clear cover, yellow cover, nectarine diffused cover and for open sun are shown in Figure 4.4. The figure shows that there was no distinct difference between the predicted and the actual moisture ratio values for all the four drying conditions. This further confirms that the Page model achieved satisfactory prediction levels as compared to the other models.

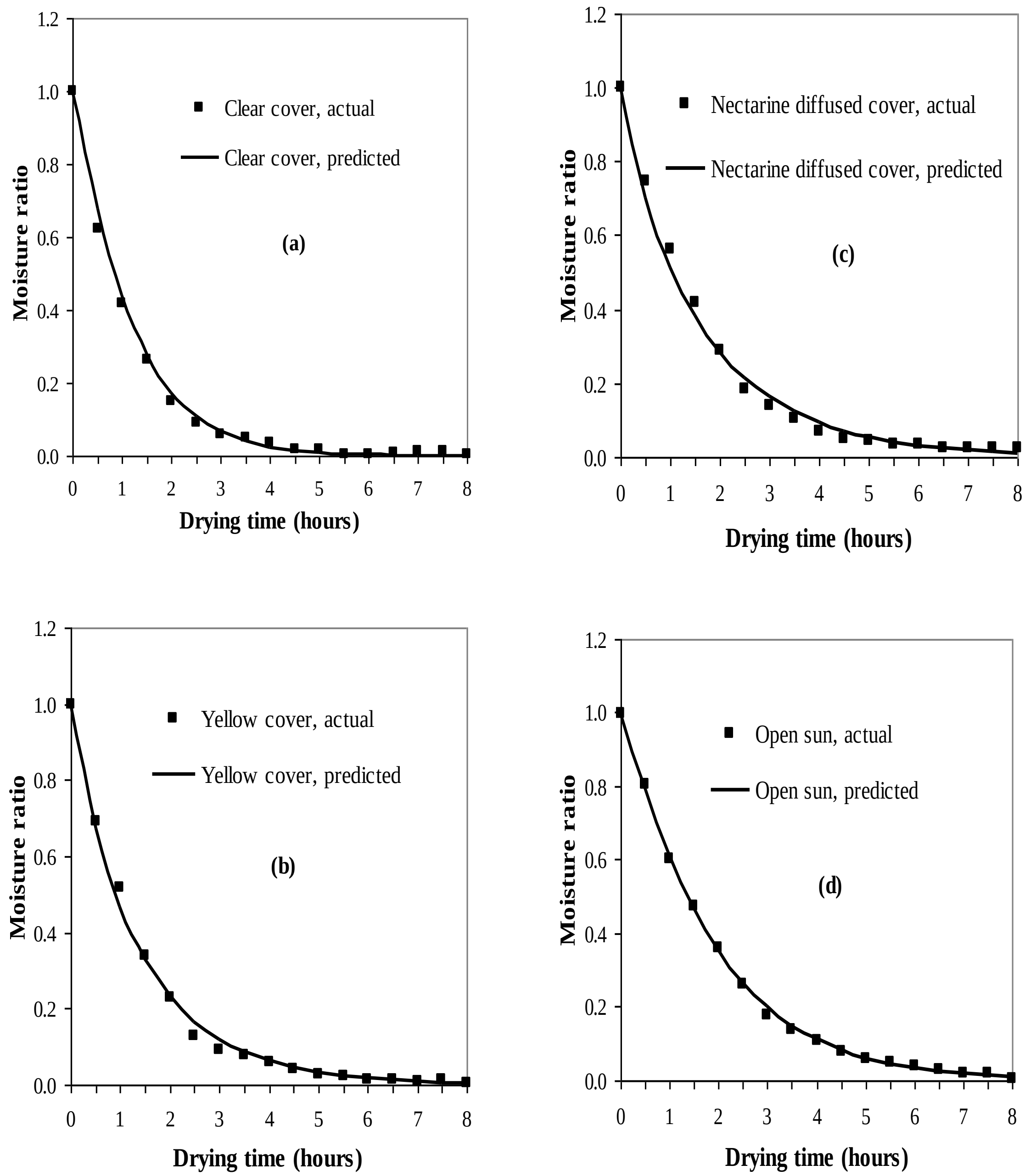

Figure 4.4 Comparison between the predicted moisture ratios using the Page model and actual values for model solar tent dryer with clear (a), yellow (b) and nectarine diffused (c) cover materials, and for open sun (d).

4.3.2 Model Evaluation in the Actual Solar Tent Dryer and the Open Sun

The preceding section dealt with modeling of thin layer drying of amaranth grains in the model solar tent dryers cover with different cover materials. This section deals with modeling of thin layer drying of amaranth grains in the actual solar tent dryer covered with yellow PVC material. Although the mean temperature and relative humidity values developed in the dryer covered with the clear PVC material were slightly higher than those for the yellow material, the values were not significantly different. Hence, since the actual dryer had already been covered with the yellow PVC material, it was decided that the study be conducted under this condition.

4.3.2.1 Drying Characteristics of Amaranth Grains in the Solar Tent Dryer and the Open Sun

In order to enable the modeling of thin layer drying of amaranth grains, temperature, relative humidity and moisture content data (Appendix Tables A7 and A8) were acquired within the dryer at two levels (i.e., Layer 1 and Layer 2) and in the open sun. Figure 4.5 compares the temperature attained in the solar tent dryer and the open sun. The temperatures attained in Layer 2 were always higher (48.9±4.8^{o}C) than those in Layer 1 (39.5±3.8^{o}C). This is due to the fact that Layer 2 was closer to the solar energy harnessing surface than Layer 1. Comparison of the temperatures attained in the dryer and the open sun shows the temperatures in the dryer (44.2±6.4^{o}C) were higher than those in the open sun (27.8±2.6^{o}C) over the entire drying period. Figure 4.5 also shows that an increase in solar radiation led to increase in temperature, indicating a direct relationship between solar radiation and temperature developed both in the dryer and the open sun. The mean value of ten-year (1996-2005) solar radiation data obtained from world satellite map (NASA) was approximately 6 kW/m^2. This NASA value was based on about 7 sunshine hours per day and was slightly lower than the sum of hourly results of solar radiation (≈ 8 kW/m^2) computed using equations (2.1)–(2.6) (Appendix Tables A9 and A10).

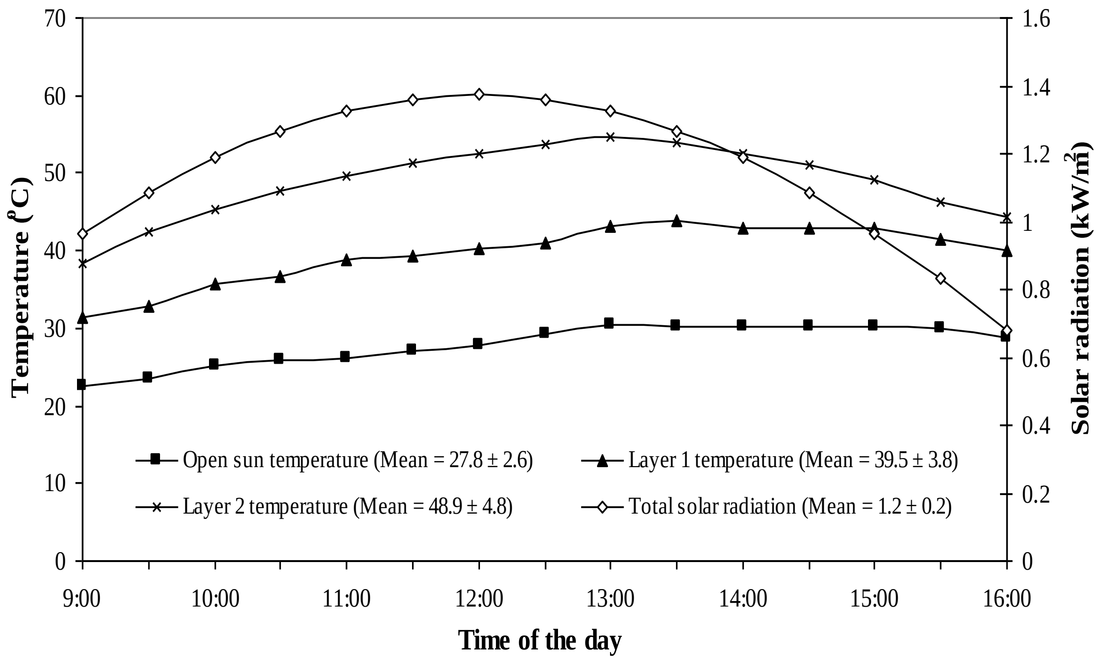

Figure 4.5 Comparison of temperature and total solar radiation with time in the solar tent dryer and the open sun.

Results of statistical analysis of temperatures attained in the dryer and the open sun during drying of amaranth grains using ANOVA at 5% level of significance are presented in Tables 4.17 and 4.18. The results in Table 4.17 show that there was a significant difference (*p*-value, 2.44×10^{-06}; $F_{critical}$, 4.196; $F_{computed}$, 34.737) between temperatures developed in Layers 1 and 2. This is a contradiction between these results and those obtained in Section 4.1 that dealt with distribution of temperature in the empty dryer. When grains were spread on Layer 2, they caused shading on Layer 1 and this may have resulted in significant lowering of temperatures on this layer. The results in Table 4.18 similarly show that there was a significant difference (*p*-value, 1.26×10^{-17}; $F_{critical}$, 3.220; $F_{computed}$, 112.963) between temperatures developed in the dryer and the open sun. This further confirms that solar tent dryers can effectively be used to harness solar energy for drying of agricultural products (Sacilik *et al.*, 2006; Abalone *et al.*, 2006) such as amaranth grains.

Table 4.17 ANOVA results corresponding to temperatures in Layers 1 and 2 of the actual solar tent dryer

Source of Variation	*s.s.*	*d.f.*	*m.s.*	$F_{computed}$	*p-value*	$F_{critical}$
Layers	650.5	1	650.5	34.737	2.44×10^{-06}	4.196
Residual	524.4	28	18.7			
Total	1174.9	29				

Table 4.18 ANOVA results corresponding to temperatures in Layers 1 and 2 of the solar tent dryer and the open sun

Source of Variation	*s.s.*	*d.f.*	*m.s.*	$F_{computed}$	*p-value*	$F_{critical}$
Drying condition	3339.0	2	1669.5	112.963	1.26×10^{-17}	3.220
Residual	620.7	42	14.8			
Total	3959.8	44				

Figure 4.6 presents the relative humidity values recorded in the solar tent dryer and the open sun. The mean relative humidity values in the dryer were consistently lower (25.6±4.3%) than those in the open sun (29.5±5.4%) during the entire drying period.

These results are similar to those obtained in Section 4.2 for the model solar tent dryers and the open sun. However, an ANOVA (Table 4.19) conducted on the results indicated that there was no significant difference between the relative humidity values for the dryer and the open sun (p-value, 0.039; $F_{critical}$, 3.220; $F_{computed}$, 3.497). The results obeyed the commonly observed behaviour that relative humidity decreases with increase in temperature (Basunia and Abe, 2001).

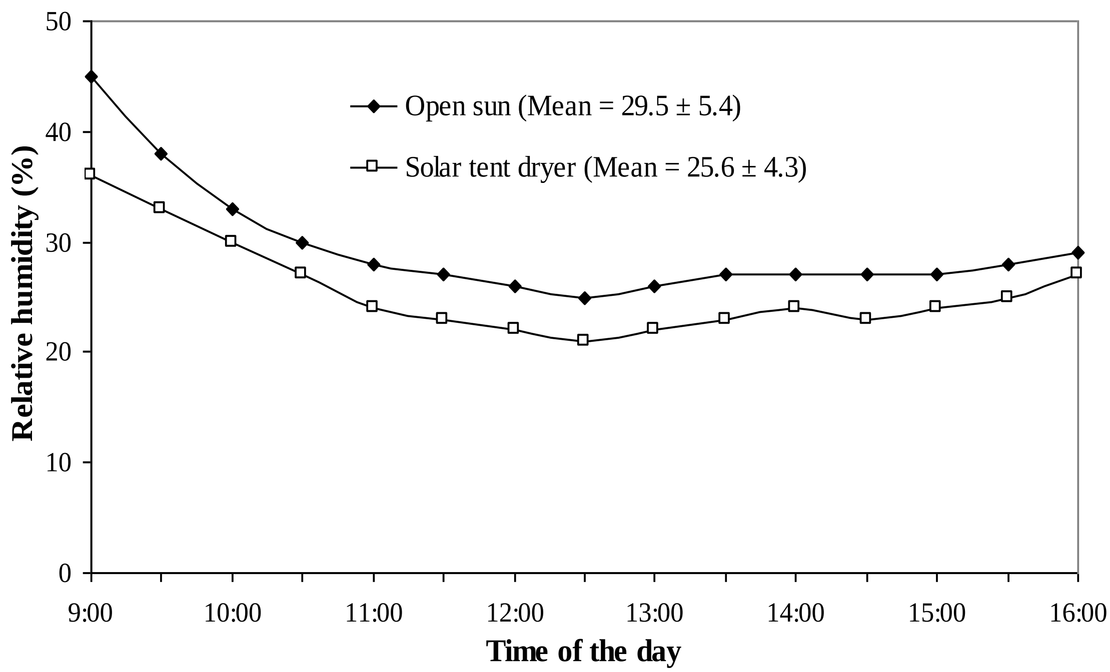

Figure 4.6 Relative humidity in the solar tent dryer and the open sun during drying of amaranth grains.

Regression analysis relating the temperature (T_i) developed in the solar tent dryer with open sun temperature (T_a) and solar radiation (I_t) yielded a linear relationship (equation (4.1)). Similarly, a linear relationship was obtained that related relative humidity, Rh_i, inside the solar tent dryer with the relative humidity, Rh_a, in the open sun and total solar radiation, I_t (equation (4.2)). The high R^2 values (>0.95) obtained imply that there is a strong correlation between the drying conditions inside the solar tent dryer and those in the open sun.

$$T_i = 1.38T_a + 14.66I_t - 6.27 \qquad (R^2 = 0.99) \qquad (4.1)$$

$$Rh_i = 0.74Rh_a - 2.62I_t + 6.63 \qquad (R^2 = 0.96) \qquad (4.2)$$

Table 4.19 ANOVA results corresponding to relative humidity values in the actual solar tent dryer and the open sun

Source of Variation	*s.s.*	*d.f.*	*m.s.*	$F_{computed}$	*p-value*	$F_{critical}$
Drying condition	154.7	2	77.4	3.497	0.039	3.220
Residual	928.9	42	22.1			
Total	1083.6	44				

The drying curves of amaranth grains in Layers 1 and 2 of the actual solar tent dryer and the open sun are shown in Figure 4.7. The individual drying curves for both layers in the dryer and the open sun are shown in Appendix Figure B2. In all cases, the moisture content decreased continuously with time. Many researchers (Basunia and Abe, 2001; Abalone *et al.*, 2006; Omid *et al.*, 2006) have noted the same trend, particularly, for cereal grains. The results show that under all the three drying conditions (viz., open sun, Layer 1 and Layer 2) the rate of drying was highest within the first 2.5 hours of drying. The drying rate reduced significantly for the subsequent hours of drying. Further, the results show that amaranth grains with initial moisture content ranging from 61.3–66.7% d.b dried to an equilibrium moisture content of 7% d.b. It took 3.5, 4.5 and 6 hours to attain the equilibrium moisture content for Layer 2, Layer 1 and open sun, respectively. It is also shown by the drying curves that the entire thin layer drying process of amaranth grains obeyed the falling rate period (Diamente and Munro, 1993).

When Layers 1 and 2 are compared, it is noticed that the drying rate was higher for the latter than the former at any given time (Figure 4.7). This is because Layer 2 attained high drying temperatures as compared to Layer 1. Similarly, the drying rate was high for the dryer than the open sun. The temperatures recorded in the dryer were higher than those in the open sun. In addition, the relative humidity values were lower in the dryer than in the open sun. The higher the temperature and the lower the relative humidity, the faster the drying (Ronoh *et al*., 2009; Sacilik *et al*., 2006).

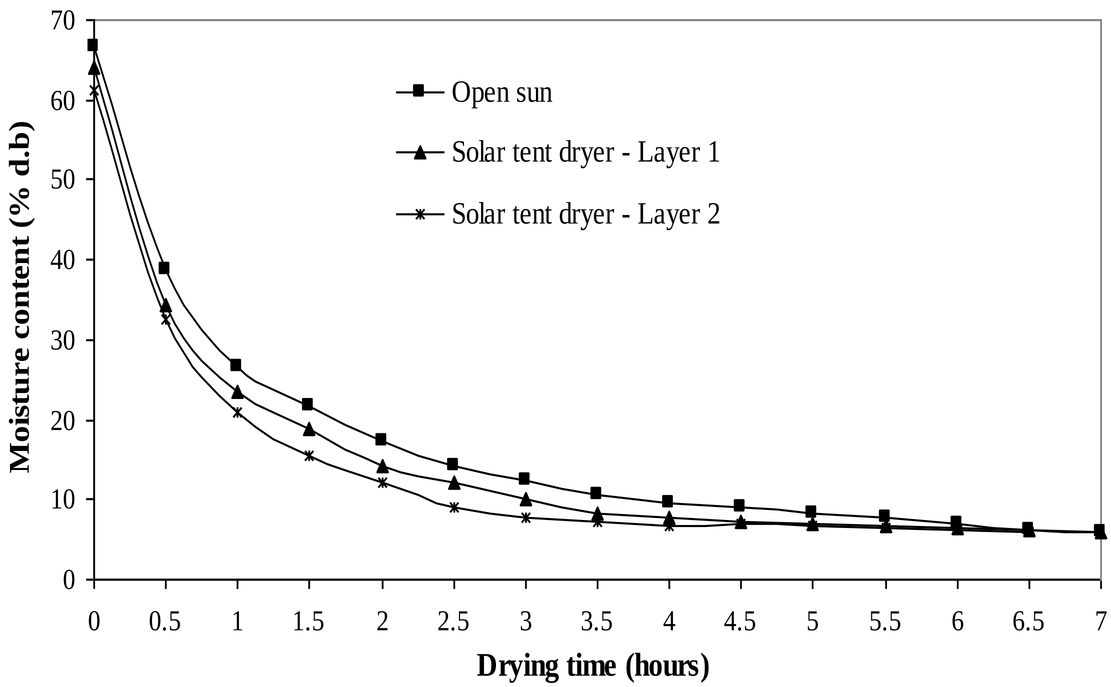

Figure 4.7 Drying curves for amaranth grains dried under open sun and in the solar tent dryer.

An ANOVA conducted on the drying data at 5% level of significance yielded the results shown in Tables 4.20–4.22. The results in Table 4.20 show that for the first 2.5 hours of drying the drying rates were not significantly different under the solar tent dryer and the open sun (*p*-value, 0.881; $F_{critical}$, 3.682; $F_{computed}$, 0.127). During this drying period there is sufficient energy and relative humidity to dry the grains under both conditions, a characteristic of the first falling rate drying period (Omid *et al.*, 2006). Conversely, Table 4.21 shows that the drying rates for the solar dryer and the open sun were slightly different between 2.5–8 hours of drying (*p*-value, 0.033; $F_{critical}$, 3.403; $F_{computed}$, 3.934). The slight difference can be attributed to the difference in energy and humidity levels recorded under both drying conditions as reported earlier in this section.

Table 4.20 ANOVA results corresponding to moisture content of amaranth grains in Layers 1 and 2 of the solar tent dryer and in the open sun within the first 2.5 hours of drying

Source of Variation	*s.s.*	*d.f.*	*m.s.*	$F_{computed}$	*p-value*	$F_{critical}$
Drying condition	96.5	2	48.2	0.127	0.881	3.682
Residual	5677.5	15	378.5			
Total	5774.0	17				

Table 4.21 ANOVA results corresponding to moisture content of amaranth grains in Layers 1 and 2 of the solar tent dryer and in the open sun after 2.5 hours of drying

Source of Variation	*s.s.*	*d.f.*	*m.s.*	$F_{computed}$	*p-value*	$F_{critical}$
Drying condition	16.8	2	8.4	3.934	0.033	3.403
Residual	51.3	24	2.1			
Total	68.1	26				

When the drying rates for Layer 1, Layer 2 and the open sun are compared for the entire drying period, it is evident that there was no significant difference among them as shown in Table 4.22 (*p*-value, 0.837; $F_{critical}$, 3.220; $F_{computed}$, 0.179). Although the preceding findings imply that there is no need for employing a solar tent dryer vis-a-vis the open sun for drying amaranth grains, as noted earlier extra energy and favourable relative humidity conditions are required to dry the grains to equilibrium moisture content. This extra energy and conducive relative humidity can sufficiently be provided by the solar tent dryer as opposed to the open sun. Similar observations have been noted by Basunia and Abe (2001) during thin layer drying of rough rice under natural convection.

Table 4.22 ANOVA results corresponding to moisture content of amaranth grains in Layers 1 and 2 of the solar tent dryer and in the open sun

Source of Variation	*s.s.*	*d.f.*	*m.s.*	$F_{computed}$	*p-value*	$F_{critical}$
Drying condition	87.6	2	43.8	0.179	0.837	3.220
Residual	10286.0	42	244.9			
Total	10373.6	44				

Comparison of the drying rates on Layers 1 and 2 of the solar dryer within the first 2.5 hours of drying shows no significant difference (p-value, 0.819; $F_{critical}$, 4.965; $F_{computed}$, 0.055) as presented in Table 4.23. Similarly, the ANOVA results in Table 4.24 show no significant difference (p-value, 0.201; $F_{critical}$, 4.494; $F_{computed}$, 1.776) in the drying rates between 2.5–8 hours of drying on Layers 1 and 2. These results, therefore, show that Layers 1 and 2 of the solar tent dryer can be used to dry amaranth grains in thin layers without significantly affecting the drying rate of the grains.

Table 4.23 ANOVA results corresponding to moisture content of amaranth grains in Layers 1 and 2 of the solar tent dryer within the first 2.5 hours of drying

Source of Variation	*s.s.*	*d.f.*	*m.s.*	$F_{computed}$	*p-value*	$F_{critical}$
Drying condition	20.9	1	20.9	0.055	0.819	4.965
Residual	3776.9	10	377.7			
Total	3797.8	11				

Table 4.24 ANOVA results corresponding to moisture content of amaranth grains in Layers 1 and 2 of the solar tent dryer after 2.5 hours of drying

Source of Variation	*s.s.*	*d.f.*	*m.s.*	$F_{computed}$	*p-value*	$F_{critical}$
Drying condition	1.6	1	1.6	1.776	0.201	4.494
Residual	14.7	16	0.9			
Total	16.3	17				

The high drying rates for amaranth grains were attained when drying using the solar tent dryer as opposed to the open sun. These rates were found to be significantly different beyond 2.5 hours of drying. Comparison of Layers 1 and 2 in the solar tent dryer shows that the drying rates were not significantly different, although the rates achieved for the latter were higher than for the former. In addition, it took 3.5 hours to dry amaranth grains from an initial moisture content of 61.3–66.7% d.b to the equilibrium moisture content of 7% d.b for Layer 2 as compared to 4.5 and 6 hours for Layer 1 and the open sun, respectively. The high drying rate also gives a high throughput (≈ 7 kg of harvested grains) in each of the vertical layers of the tent dryer. These findings demonstrate the potential of applying natural convection solar tent dryers to enhance harnessing of solar energy for drying of amaranth grains. The results further show that the capacity of drying can be increased by drying the grains in vertical layers without significantly affecting the drying rate.

4.3.2.2 Modeling Thin Layer Solar Drying of Amaranth Grains in the Actual Solar Tent Dryer and the Open Sun

Regression analysis was conducted for the same six drying models considered in Section 4.3.1. This analysis related the drying time and moisture ratio to select the model that best describes thin layer drying of amaranth grains. The model coefficients and parameters of error analysis obtained for the natural convection solar tent dryer and the open sun are presented in Tables 4.25–4.27. Two levels (viz., Layer 1 and Layer 2) of drying were used in the solar tent dryer. The acceptability of the model was based on $R^2 \cong 1$, and low values of χ^2 and RMSE.

When all the six thin layer drying models are considered, the results show that the R^2 values obtained for the solar tent dryer in Layer 1 and Layer 2, and the open sun ranged from 0.858–0.998, 0.834–0.999 and 0.878–0.997, respectively. The corresponding values for the RMSE were 0.0118–0.0979, 0.0055–0.1065 and 0.0003–0.0095, respectively. The χ^2 values were in the range of 0.0002–0.0111, 0.0000–0.0131 and 0.0154–0.0908, respectively. Comparison of the six models shows that the Page model attained the highest R^2 (0.997–0.999) and the lowest RMSE (0.0003–0.0118) and χ^2 (0.0000–0.0154) values. This indicates that the Page model satisfactorily predicted the thin layer drying of amaranth grains better than the other models.

Table 4.25 Estimated parameters and comparison criteria of moisture ratio for the open sun

Model	**Model coefficients and constants**	R^2	**RMSE**	χ^2	**ε (%)**	η_p**(%)**
Newton	k = 0.7803	0.963	0.0027	0.0500	9.5 ± 7.3	40.0
Page	k = 0.99, n = 0.8141	0.997	0.0003	0.0154	5.7 ± 3.1	40.0
Modified Page	k = 0.99, n = 0.8141	0.996	0.0003	0.0154	5.8 ± 3.1	40.0
Henderson & Pabis	a = 1.0235, k = 0.7803	0.954	0.0036	0.0555	10.1 ± 8.0	40.0
Logarithmic	a = 0.7585, k = 0.7792, c = 0.0187	0.949	0.0043	0.0589	7.5 ± 7.4	53.3
Wang & Singh	a = -0.3125, b = 0.0310	0.878	0.0095	0.0908	30.4 ± 20.8	6.7

Table 4.26 Estimated parameters and comparison criteria of moisture ratio for Layer 1 of the solar tent dryer

Model	**Model coefficients and constants**	**R^2**	**RMSE**	**χ^2**	**ε (%)**	**η_p(%)**
Newton	k = 0.8341	0.948	0.0594	0.0038	9.9 ± 10.6	46.7
Page	k = 1.1494, n = 0.8171	0.998	0.0118	0.0002	3.1 ± 2.3	80.0
Modified Page	k = 1.1494, n = 0.8171	0.997	0.0128	0.0002	2.9 ± 2.4	73.3
Henderson & Pabis	a = 0.8105, k = 0.8341	0.960	0.0521	0.0031	4.6 ± 4.6	73.3
Logarithmic	a = 0.*7333*, k = 0.8446, c = 0.0053	0.932	0.0679	0.0058	4.4 ± 5.9	66.7
Wang & Singh	a = -0.3249, b = 0.0334	0.858	0.0979	0.0111	34.5 ± 22.5	6.7

Table 4.27 Estimated parameters and comparison criteria of moisture ratio for Layer 2 of the solar tent dryer

Model	**Model coefficients and constants**	**R^2**	**RMSE**	**χ^2**	**ε (%)**	**η_p(%)**
Newton	k = 0.8816	0.936	0.0662	0.0047	15.9 ± 14.7	46.7
Page	k = 1.2969, n = 0.8219	0.999	0.0055	0.0000	2.9 ± 2.0	80.0
Modified Page	k = 1.2969, n = 0.8219	0.998	0.0097	0.0001	4.0 ± 3.8	66.7
Henderson & Pabis	a = 0.6337, k = 0.8816	0.864	0.0966	0.0108	6.0 ± 8.4	66.7
Logarithmic	a = 0.7277, k = 0.9044, c = -0.0049	0.927	0.0705	0.0062	8.4 ± 6.3	33.3
Wang & Singh	a = -0.3347, b = 0.0353	0.834	0.1065	0.0131	40.8 ± 24.6	6.7

Tables 4.25–4.27 further present the mean absolute residual errors and the corresponding standard deviations achieved by the six drying models. The computed results of absolute residual errors for moisture ratio of amaranth grains under Layers 1

and 2 of the dryer and the open sun are presented in Appendix Tables A15–A17. When the models are compared, the results show that the Page model attained the lowest mean residual errors ranging from 2.9±2.0–5.7±3.1%. The low corresponding standard deviations illustrate uniformity in prediction level of this model (Kanali, 1997). The results, therefore, confirm that the Page model attained satisfactory prediction level for thin layer drying of amaranth grains as compared to other models.

The prediction performances of the drying models are also shown in Tables 4.25–4.27. The prediction performance was based on a ±5% residual error interval. It is seen from the tables that the Page model attained the highest prediction performances of 80.0% for Layers 1 and 2 of the solar tent dryer. However, the prediction performances for all the models in the open sun were relatively low (6.7–53.3%) as compared with the solar tent dryer. The Page model attained 40% prediction performance which was slightly lower than that of Logarithmic model (53.3%). With reference to all the parameters used for selection, the Page model best described thin layer drying of amaranth grains in the solar tent dryer and the open sun.

Comparison of the moisture ratios predicted by the Page model and the actual values for Layers 1 and 2 of the solar tent dryer, and for open sun is shown in Figure 4.8. It is noticed from the figure that there was indistinct difference between the predicted and the actual moisture ratio values. This further confirms the superiority of the Page model over the other models in predicting thin layer drying of amaranth grains in the solar tent dryer and the open sun.

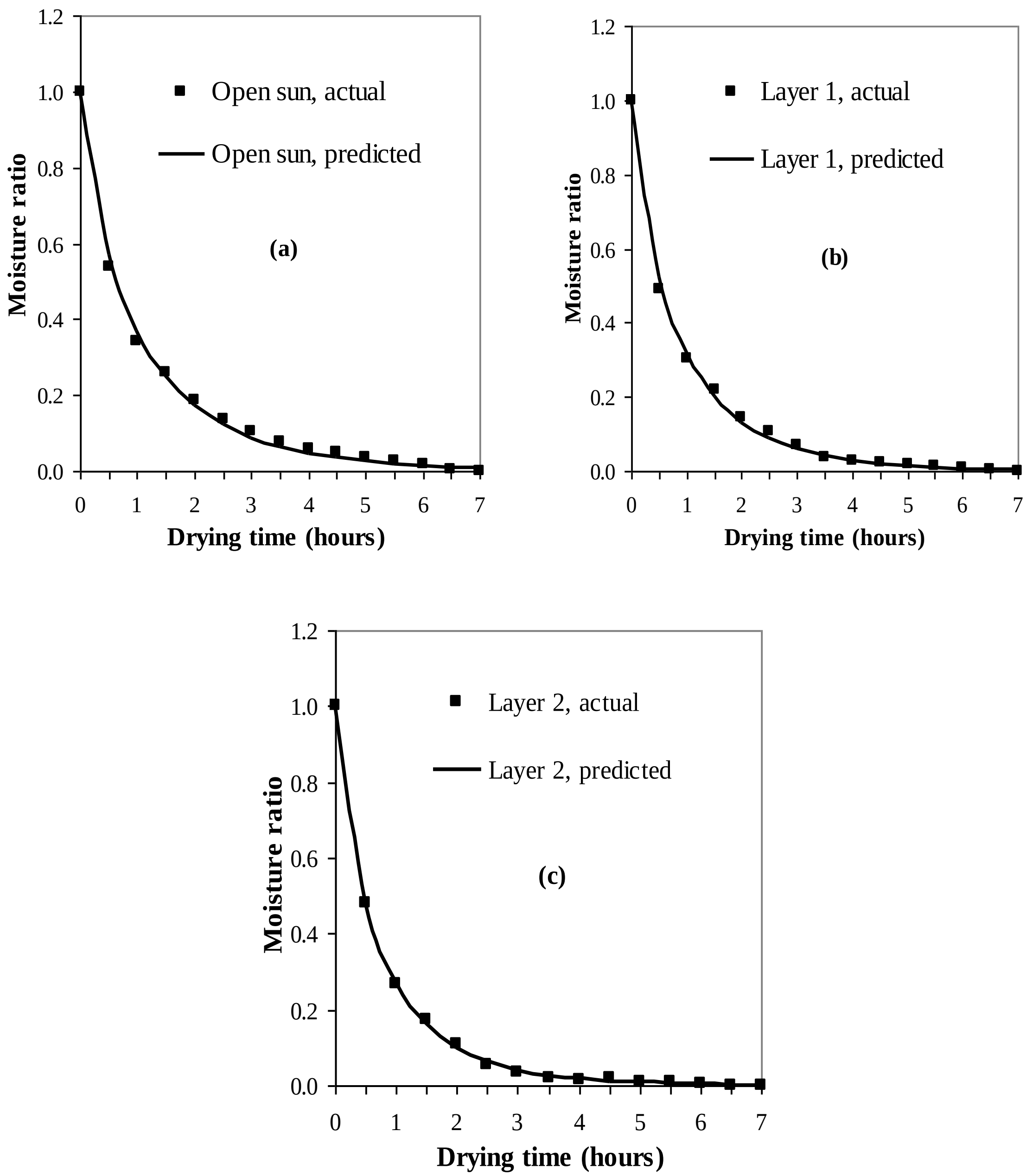

Figure 4.8 Comparison between the predicted moisture ratios using Page model and the actual values for the open sun (a) and Layers 1 (b) and 2 (c) of the solar tent dryer.

4.3.3 Estimation of Effective Moisture Diffusivity

The effective moisture diffusivity (D_e) values of amaranth grains dried under the model dryers with nectarine diffused, yellow and clear cover materials were found to be 3.45×10^{-12}, 4.29×10^{-12} and 4.60×10^{-12} m^2s^{-1}, respectively. The corresponding value for the open sun was 4.04×10^{-12} m^2s^{-1}. The effective moisture diffusivity was highest for the model dryer with the clear cover in which high temperatures were attained. Previous studies show that increase in temperature leads to increase in moisture removal from cereal grains (Sacilik and Elicin, 2006).

In the actual solar tent dryer, the D_e values of amaranth grains attained for Layers 1 and 2 were 5.88×10^{-12} and 6.20×10^{-12} m^2s^{-1}, respectively, while for the open sun the value was 5.49×10^{-12} m^2s^{-1}. The diffusivity values obtained are of the same order of magnitude as those previously reported for amaranth grain (Vizcarra-Mendoza *et al*., 2003). The higher temperatures attained in Layer 2 of the solar tent dryer led to highest D_e value and this shows how temperature strongly influences the mechanism of moisture removal from amaranth grains. The effective moisture diffusivities calculated from the drying data represented an overall mass transport property of moisture in the material, which include liquid diffusion, vapour diffusion or any other possible mass transfer mechanism. The continuous decrease in moisture ratio with increase in drying time showed that the results can be interpreted using Fick's diffusion model (Konishi *et al*., 2001).

4.4 Effect of Colour of Cover Material on Physical, Optical and Nutritive Properties of Amaranth Grains

4.4.1 Effect of Colour of Cover Material on Hardness of Amaranth Grains

The hardness of amaranth grains was measured as the force required to break the grains. Table 4.28 shows the hardness values for amaranth grains dried under the different cover materials and the open sun. The types of cover materials for the dryers were clear, yellow and nectarine diffused, all of which had the same thickness (Appendix Table A18). The hardness values ranged from 2.15–2.23 kg for the model dryers while an average value of 2.23 kg was achieved for the open sun. The yellow cover achieved slightly low mean hardness values (2.15±0.14) as compared with the other materials. The standard deviations for the mean hardness values obtained for all the cover materials were low and they ranged from 0.12–0.16 kg. This shows that there was uniformity in hardness values obtained for amaranth grains.

Table 4.28 Hardness and colour parameters for amaranth grains dried under different cover materials and the open sun

Type of cover material	**Hardness (kg)**	**Colour parameters**			
		L*	***a****	***b****	***h****
Yellow	2.15±0.14	52.83±0.83	7.68±0.18	39.31±1.07	78.94±0.43
Nectarine diffused	2.23±0.12	53.35±0.90	7.32±0.44	37.41±1.00	78.93±0.74
Clear	2.20±0.13	54.15±0.61	7.24±0.37	37.71±1.78	79.15±0.19
No cover (open sun)	2.23±0.16	54.20±0.33	7.25±0.16	36.57±0.43	78.78±0.37

Mean value ± standard deviation

An ANOVA (Table 4.29) conducted on the data at 5% level of significance showed that there was no significant difference (p-value, 0.542; $F_{critical}$, 3.682; $F_{computed}$, 0.638) in the hardness for amaranth grains dried under the different cover materials. Similarly, there was no significant difference (p-value, 0.695; $F_{critical}$, 3.098; $F_{computed}$, 0.488) between the hardness values for grains dried under the different cover materials and the open sun (Table 4.30).

Table 4.29 ANOVA results corresponding to hardness values of amaranth grains dried under different cover materials

Source of Variation	*s.s.*	*d.f.*	*m.s.*	$F_{computed}$	*p-value*	$F_{critical}$
Cover material	0.02	2	0.01	0.638	0.542	3.682
Residual	0.25	15	0.02			
Total	0.27	17				

Table 4.30 ANOVA results corresponding to hardness values of amaranth grains dried under different cover materials and the open sun

Source of Variation	*s.s.*	*d.f.*	*m.s.*	$F_{computed}$	*p-value*	$F_{critical}$
Drying condition	0.03	3	0.01	0.488	0.695	3.098
Residual	0.38	20	0.02			
Total	0.41	23				

4.4.2 Effect of Colour of Cover Material on Colour of Amaranth Grains

As shown in Table 4.28, the L^*, a^* and b^* values for amaranth grains dried under the different cover materials ranged from 52.83–54.20, 7.24–7.68 and 36.57–39.31, respectively. Amaranth grains dried in the open sun achieved slightly higher L^* value (54.20±0.33) and lower values of a^* (7.25±0.16) and b^* (36.57±0.43) parameters as compared to those for the different cover materials.

The L^*, a^* and b^* parameters were utilized in computing the h^* values based on equation (3.9) and the results are also presented in Table 4.28. The results indicate that the computed h^* values of amaranth grains were in the range of 78.78–79.15^o for all the drying conditions (viz., the three cover materials and the open sun). The clear cover achieved the highest h^* value while the open sun registered the lowest. The colour parameters are related to the browning reaction where a decrease in L^* values, an increase in a^* values and a decrease in h^* values indicate more browning (Rocha and Morais, 2003; Hawlader *et al*., 2006). Hence, the preceding results imply that the clear cover material had less browning effect on the grains during drying as compared with the other materials and the open sun.

At 5% level of significance, ANOVA (Table 4.31) showed no significant difference (p-value, 0.702; $F_{critical}$, 3.682; $F_{computed}$, 0.362) in hue angles for grains dried under different cover materials. Further comparison of the hue angles of grains dried under different cover materials and the open sun (Table 4.32) also showed no significant difference (p-value, 0.616; $F_{critical}$, 3.098; $F_{computed}$, 0.610). Generally an increase in temperature led to increase in hue angle, as also noted by Hii *et al*. (2009).

Table 4.31 ANOVA results corresponding to hue angles of amaranth grains dried under different cover materials

Source of Variation	*s.s.*	*d.f.*	*m.s.*	$F_{computed}$	*p-value*	$F_{critical}$
Cover material	0.2	2	0.1	0.362	0.702	3.682
Residual	3.8	15	0.3			
Total	4.0	17				

Table 4.32 ANOVA results corresponding to hue angles of amaranth grains dried under different cover materials and the open sun

Source of Variation	*s.s.*	*d.f.*	*m.s.*	$F_{computed}$	*p-value*	$F_{critical}$
Drying condition	0.4	3	0.1	0.610	0.616	3.098
Residual	4.5	20	0.2			
Total	4.9	23				

4.4.3 Effect of Colour of Cover Material on Crude Protein Content of Amaranth Grains

The results presented in Table 4.33 show that the percentage crude protein content of amaranth grains is a function of the percentage of nitrogen found in the grains. The mean values of crude protein content ranged from 17.07–17.21% for the grains dried under different cover materials while a mean value of 17.54% was obtained for the open sun. The corresponding standard deviations ranging from 0.09–0.31% were low, which confirmed uniformity in the percentage crude protein contents of amaranth grains.

Table 4.33 Comparison of crude protein content of amaranth grains dried under different cover materials and the open sun

Type of cover material	**Crude protein content (%)**
Yellow cover	17.08±0.17
Nectarine diffused cover	17.21±0.20
Clear cover	17.07±0.09
No cover (open sun)	17.54±0.31

Mean value ± standard deviation

An ANOVA (Table 4.34) conducted at 5% level of significance showed no significant difference (*p*-value, 0.299; $F_{critical}$, 3.682; $F_{computed}$, 1.310) in crude protein content for the different cover materials. Similarly, comparison of crude protein content for grains dried under the different cover materials and the open sun (Table 4.35) showed no significant difference (*p*-value, 0.067; $F_{critical}$, 3.098; $F_{computed}$, 2.783).

Table 4.34 ANOVA results corresponding to crude protein content of amaranth grains dried under different cover materials

Source of Variation	*s.s.*	*d.f.*	*m.s.*	$F_{computed}$	*p-value*	$F_{critical}$
Cover material	0.1	2	0.03	1.310	0.299	3.682
Residual	0.4	15	0.03			
Total	0.5	17				

Table 4.35 ANOVA results corresponding to crude protein content of amaranth grains dried under different cover materials and the open sun

Source of Variation	*s.s.*	*d.f.*	*m.s.*	$F_{computed}$	*p-value*	$F_{critical}$
Drying option	0.2	3	0.07	2.783	0.067	3.098
Residual	0.5	20	0.02			
Total	0.7	23				

Although higher temperatures prevailed in the dryer with the clear cover, the nutritive value of amaranth grain in terms of crude protein content was not significantly affected. The results for crude protein content of amaranth grains were satisfactory as they ranged between 16 and 18% (Abalone *et al*., 2006). The crude protein content in grains dried in the open sun was slightly higher than for those dried under the different cover materials. This is an indication that high temperatures may denature proteins in the grains (Hii *et al*., 2009).

CHAPTER FIVE

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The study reported herein was conducted with the overall objective of analyzing thin layer drying characteristics of amaranth grains in a natural convection solar tent dryer. The results demonstrate that solar tent dryers can be employed to enhance thin layer drying of amaranth grains in Kenya. The specific conclusions drawn from the study were as follows:

1) There was no significant difference in the distribution of temperature within and between Planes 1 and 2 that were spaced at 0.75 and 1.5 m above the ground concrete surface of the solar tent dryer, respectively. However, high mean temperatures in the range of 38.8–39.2^{o}C were developed at Plane 2 as compared to 38.2–38.4^{o}C achieved in Plane 1.
2) The grains in the dryer with the clear cover PVC material attained the highest drying rates as opposed to those in the yellow and nectarine diffused cover materials. The clear cover material attained the highest temperatures (44.5±5.8^{o}C) and lowest relative humidity (23.5±6.5%) values. In addition, the solar tent dryer successfully dried the grains to an equilibrium moisture content of 7% d.b after 4.5 hours of drying as opposed to 7 hours for the open sun.
3) Comparison of the coefficient of determination (R^2), root mean square error (RMSE), reduced chi-square (χ^2), absolute residual errors and prediction performance shows that the Page model best described thin layer drying of amaranth grains in conventional solar tent dryer and the open sun. The Page model had the highest R^2 (0.994–0.999) and lowest values of RMSE (0.0003–0.0240) and

χ^2 (0.0000–0.0154). In addition, the low mean residual errors (2.9±2.0–10.6±6.7) and high prediction performance (80.0–88.2%) obtained for the Page model confirmed its superiority over the other models in predicting the thin layer drying of amaranth grains in a natural convection solar tent dryer and the open sun.

4) Based on the physical and chemical analyses, the colour of cover material had no significant effect (p>0.05) on hardness, colour and crude protein content properties of amaranth grains during thin layer drying.

5.2 Recommendations

This study identified some key areas which require further investigation. It is therefore recommended that:

1) Since monitoring of temperature distribution was only based on the identified discrete points on Planes 1 and 2, further tests be conducted to monitor the distribution of temperature in the entire drying space of the solar tent dryer.
2) The optimum vertical spacing between the drying layers during thin layer drying be determined in order to enhance the dryer capacity.
3) The analysis considers other properties of PVC cover material such as thickness and their effects on quality parameters of the grains. The performance of other cover materials with different properties should be investigated with respect to thin layer solar tent drying of amaranth grains.
4) A study be carried out in a controlled environment to determine the effect of temperature, relative humidity and velocity of drying air on quality and drying rates of amaranth grains in the solar tent dryer.

5) Further investigation be conducted in order to model the whole drying process from the solar energy intake to the drying of amaranth grains in a solar tent dryer.

REFERENCES

Abalone, R., Cassinera, A., Gastón, A. and Lara, M.A. (2004). Some physical properties of amaranth seeds. Biosystems Engineering, 89(1): 109–117.

Abalone, R., Cassinera, A., Gastón, A. and Lara, M.A. (2006). Thin layer drying of amaranth seeds. Biosystems Engineering, 93(2): 179–188.

Agribusiness Development Centre. (2001). ADC Commercialisation bulletin #11: Dried fruit. Kampala, Uganda.

Ajwang, P. (2005). Prediction of the effects of insect-proof screens on the climate in naturally ventilated greenhouses in the humid tropics. PhD Thesis, University of Hannover, Germany.

Akpinar, E.K. (2005). Mathematical modeling of thin layer drying process under open sun of some aromatic plants. Journal of Food Engineering, 77: 864-870.

Al-Ajlan, S.A., Al-Faris, H. and Khonkar, H. (2003). A simulation modeling for optimization of flat plate collector design in Riyadh, Saudi Arabia. Renewable Energy, 28: 1325–1339.

Arinze, E.A. (1987). Solar energy for crop drying in developing countries. Solar Drying in Africa, Proceedings of a workshop held in Dakar, Senegal, 21st–24th July 1986, IDRC, Ottawa, Canada, pp. 128.

Bala, B.K. (1997). Drying and storage of cereal grains. Science Publishers, Inc., Plymouth, UK.

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

Bateman, P.L. (1994). Postharvest losses in grains. World Agriculture, Sterling Publications Ltd, London.

Bennamoun L. and Belhamri, A. (2003). Design and simulation of a solar dryer for agriculture products. Journal of Food Engineering, 59: 259–266.

Blamire, J. (2003). Kjeldhal method: e-learning for quantitative analysis. Science @ a Distance. Available at: http://www.brooklyn.cuny.edu/bc/ahp/SDKC.html. [Accessed: November 20, 2009].

Bressani, R. (1988). Amaranth: the nutritive value and potential uses of the grain and by-products. Food and Nutrition Bulletin, 10(2): 49–59.

Brooker, C.W., Bakker-Arkema, F.W. and Hall, C.W. (1992). Drying and storage of grains and oilseeds. Van Nostrand Reinhold, New York, USA.

Calzetta Resio, A.N., Aguerre, R.J. and Suarez, C. (2005). Analysis of simultaneous water absorption and water-starch reaction during soaking of amaranth grain. Journal of Food Engineering, 68(2): 265–270.

Charles, E., Summers, J.W., Daniels, C.A. and Berard, M.T. (2005). PVC handbook (illustrated ed.). Hanser Verlag.

Chhninman, M.S. (1984). Evaluation of selected mathematical models for describing thin layer drying of in-shell pecans. Transactions of the ASAE, 27: 610–615.

Colson, K.H. and Young, J.H. (1990). Two-component thin layer drying model for unshelled peanuts. Transactions of the ASAE, 33(1): 241–246.

Crank, J. (1975). Mathematics of diffusion (2nd edition). London: Oxford University Press.

Diamente, L.M. and Munro, P.A. (1993). Mathematical modelling of the thin layer solar drying of sweet potato slices. Solar Energy, pp. 271–276.

Dinçer, I. (1996). Sun drying of Sultana grapes. Drying Technology, pp. 1827–1838.

Doymaz, I., Gorel, O. and Akgun, N.A. (2004). Drying characteristics of the solid by-product of olive oil extraction. Biosystems Engineering, 88(2): 213–219.

Doymaz, I. (2005). Drying behaviour of green beans. Journal of Food Engineering, 69: 161–165.

Duffie, J.A. and Beckman, W.A. (1991). Solar engineering of thermal processes. John Wiley and Sons, Inc., New York, USA.

Exell, R.H.B. (1980). Basic design theory for simple solar rice dryer. Renewable Energy Review, pp. 101–110.

Ezekoye, B.A. and Enebe, O.M. (2006). Development and performance evaluation of modified integrated passive solar grain dryer. The Pacific Journal of Science and Technology, 7(2): 185–190.

FAO Bulletin No. 109 (1994). Grain storage techniques: Evolution and trends in developing countries. Rome, Italy.

Fortes, M. and Okos, M. (1981). A non-equilibrium thermodynamics approach to heat and mass transfer in corn kernels. Transactions of the ASAE, 24(3): 761–769.

Garg, H.P. and Prakash, J. (2000). Solar energy: Fundamentals and applications. 1st Revised Ed. Tata McGraw-Hill Publishers, New Delhi, India.

Gonzalez, R.J., Torres, R.L., De-Greef, D.M., Tosi, E. and Re, E. (2002). Effects of popping and extrusion processes on some hydration properties of amaranth. Brazilian Journal of Chemical Engineering, 19(4): 391–395.

Guine, R.P.F., Ferreira, D.M.S., Barroca, M.J. and Goncalves, F.M. (2007). Study of the drying kinetics of solar-dried pears. Biosystems Engineering, 98(4): 422–429.

Gupta, V.K. (1986). Grain amaranths in Kenya. In: Proc. Third Amaranth Conf. Rodale Press, Inc., Emmaus, Pennsylvania.

Grubben, G.J.H. and Denton, O.A. (2004). Plant Resources of Tropical Africa (PROTA) 2. Vegetables. PROTA Foundation, Wageningen; Backhuys, Leiden; CTA, Wageningen.

Hawlader, M.N.A., Perera, C.O. and Tian, M. (2006). Properties of modified atmosphere heat pump dried foods. Journal of Food Engineering, 74: 392–401.

Hii, C.L., Law, C.L., Cloke, M. and Suzannah, S. (2009). Thin layer drying kinetics of cocoa and dried product quality. Biosystems Engineering, 102(2): 153–161.

Ibarz, A. and Barbosa-Canovas, G.V. (2003). Unit operations in food engineering. CRC Press.

Inprasit, C. and Noomhorm, A. (2001). Effect of drying air temperature and grain temperature of different types of dryer and operation on rice quality. Drying Technology, 19(2): 389–404.

Irving, D.W., Betschart, A.A. and Saunders, R.M. (1981). Morphological studies of *Amaranthus cruentus*. Journal of Food Science, 46(4): 1170–1174.

Kanali, C.L. (1997). Prediction of axle loads induced by sugarcane transport vehicles using statistical and neural-network models. Journal of Agricultural Engineering Research, 68(3): 207–213.

Karekezi, S. and Ranja, T. (1997). Renewable energy technologies in Africa. Longhouse Publishing Services, Cumbria, UK.

Karim, M.A. and Hawlader, M.N.A. (2004). Development of solar air collectors for drying applications. Energy Conversion and Management, 35(3): 329–345.

Kassem, A.S. (1998). Comparative studies on thin layer drying models for wheat. 13^{th} International Congress on Agricultural Engineering (Vol. 6), 2^{nd}–6^{th} February, Morocco.

Kingsly, R.P., Goyal, R.K., Manikantau, M.R. and Ilyas, S.M. (2007). Effects of Pretreatments and drying air temperature on drying behaviour of peach slices. International Journal of Food Science and Technology, 42: 65–69, Blackwell Publishing.

Konishi, Y., Horiuchi, J.I. and Kobayashi, M. (2001). Dynamic evaluation of the dehydration response curves of food characterized by a poultice-up process using a fish-paste sausage: A new tank model for computer simulation. Drying Technology, 19(7): 1271–1285.

Kristoferson, L.A. and Bokalders, V. (1991). Renewable energy technologies: their applications in developing countries. Intermediate Technologies Publications, London.

Krokida, M.K. and Maroulis, Z.B. (2000). Quality changes during drying of food materials. In: Drying Technology in Agriculture and Food Sciences, Mujumdar, A.S., ed., Science Publishers, Inc., Enfield (NH), USA.

Kudra, T. and Mujumdar, A.S. (2002). Advanced drying technologies. Marcel Dekker, Inc., New York.

Lahsasni, S., Kouhila, M., Mahrouz, M., Idlimam, A. and Jamali, A. (2004). Thin layer convective solar drying and mathematical modeling of prickly pear peel (*Opuntia ficus indica*). Energy, 29(2): 235–249.

Leon, M.A., Kumar, S. and Bhattacharya, S.C. (2002). A comprehensive procedure for performance evaluation of solar food dryers. Renewable and Sustainable Energy Reviews, 6(4): 367–393.

Liu, Q. and Bakker-Arkema, F.W. (1997). Stochastic modelling of grain drying, Part 2: Model development. Journal of Agricultural Engineering Research, 66: 275–280.

Lost Crops of Africa (2006). Volume II: Vegetables. Development, Security, and Cooperation (DSC).

McGuire, R. (1992). Reporting of objective colour measurements. Journal of Horticultural Science, 27(12): 1254–1255.

Mohandes, M., Balghonaim, A., Kassa, M., Rehman, S. and Halawani, T.O. (2000). Use of radial basis functions for estimation of monthly mean daily solar radiation. Solar Energy, 68: 161–168.

Muchena, F.N., Wamicha, W.N. and Njoroge, C.R. (1978). Detailed soil survey of Jomo Kenyatta College of Agriculture and Technology. Kenya Soil Survey, Ministry of Agriculture, pp.1–3.

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

Mwithiga, G. and Kigo, S.N. (2006). Performance of a solar dryer with limited sun tracking capability. Journal of Food Engineering, 74: 247–252.

Nindo, C.I. (1995). Studies in the sun drying of raw rough rice. PhD Thesis, Iwate University, Japan.

O'Callaghan, J.R., Menzies, D.J. and Bailey, P.H. (1971). Digital simulation of agricultural dryer performance. Journal of Agricultural Engineering Research, 16: 223–244.

Omid, M., Yadollahinia, A.R. and Rafiee, S. (2006). A thin-layer drying model for paddy dryer. Proceedings of the International conference on Innovations in Food and Bioprocess Technologies, 12th–14th December 2006, AIT, Pathumthani, Thailand.

Oosthuizen, P.H. (1987). A numerical model of a natural convection solar grain dryer: development and validation. IDRC, Ottawa, Canada.

Overhults, D.D., White, G.M., Hamilton, M.E. and Ross, I.J. (1973). Drying soybeans with heated air. Transactions of the ASAE, 16: 195–200.

Pagano, A.M. and Mascheroni, R.H. (2005). Sorption isotherms of Amaranthus grains. Journal of Food Engineering**,** 67(4): 441–450.

Prim, L. (2003). Growing and harvesting quinoa and amaranth. Newsletter #38: Seeds of Change, 29th November 2003.

Rocha, A.M.C.N. and Morais, A.M.M.B. (2003). Shelf life of minimally processed apple (cv. Jonagored) determined by colour changes. Food Control, 14: 13–20.

Ronoh, E.K., Kanali, C.L., Mailutha, J.T. and Shitanda, D. (2009). Modeling thin layer drying of amaranth seeds under open sun and natural convection solar tent dryer. Agricultural Engineering International: the CIGR Ejournal. Manuscript 1420. Vol. XI. November, 2009.

Sacilik, K. and Elicin, A.K. (2006). The thin layer drying characteristics of organic apple slices. Journal of Food Engineering, 73: 281–289.

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: 231–238.

Salunkhe, D.K., Chavan, J.K. and Kadam, S.S. (1985). Postharvest biotechnology of cereals. CRC Press, Inc., Florida.

Saleh, T. and Sarker, M.A.R. (2002). Performance of a PV operated forced convection solar energy dryer. Bangladesh University of Engineering and Technology, Bangladesh.

Saravacos, G.D. and Kostaropoulos, A.E. (2002). Handbook of food processing equipment. Kluwer Academic/Plenum Publishers, New York.

Sarsavadia, P.N., Sawhney, R.L., Pangavhane, D.R. and Singh, S.P. (1999). Drying behaviour of brined onion slices. Journal of Food Engineering, 40: 219–226.

Saunders, R.M. and Becker, R. (1985). Amaranthus: A potential food and feed resource. Advances in Cereal Science Technology (Pomeranz, E.Y., ed), Vol. 6, pp. 357–396. American Association of Cereal Chemists, St. Paul, Minnesota, USA.

Shatadal, P., Jayas, D.S. and White, N.D.G. (1990). Thin-layer drying characteristics of canola. Transactions of the ASAE, 33(3): 871–876.

Shitanda, D. and Wanjala, N.V. (2003). Effect of different drying methods on the quality of jute (*Corchorus olitorius L.*). Proceeding of the 3rd Asian-Pacific Drying Conference. Asian Institute of Technology-Bangkok, Thailand. 1st–3rd September, pp. 627–636.

Steinfeld, A. and Segal, I. (1986). A simulation model for solar thin layer drying process. Drying Technology, 4: 535–542.

Sukhatme, P.K. (2003). Solar energy: principles of thermal collection and storage. 2nd edn, Tata McGraw-Hill Publishing, New Delhi.

Tiris, C., Ozbalta, N., Tiris, M. and Dincer, I. (1994). Experimental testing of new solar dryer. International Journal of Energy Research, pp. 483–490.

Togrul, I.T. and Pehlivan, D. (2002). Mathematical modeling of solar drying of apricots in thin layers. Journal of Food Engineering, 55(3): 209–217.

Tucker, J. (1986). Amaranth: the once and future crop. Bioscience, 36(1): 9–13.

Uluko, H., Kanali, C.L., Mailutha, J.T. and Shitanda, D. (2006). A finite element model for the analysis of temperature and moisture distribution in a solar grain dryer. The Kenya Journal of Mechanical Engineering, 2(1): 47–56, Fimen Publishers, Nairobi, Kenya.

Vizcarra-Mendoza, M.G., Martinez, V.C. and Caballero, D.F. (2003). Thermal and moisture diffusion properties of amaranth seeds. Biosystems Engineering, 86(4): 441–446.

Wang, C.Y. and Singh, R.P. (1978). A single layer drying equation for rough rice. ASAE Paper No: 78–6505, St. Joseph, Michigan.

Weber, L.E. (1987). Amaranth grain production guide. Rodale Research Center, Rodale Press Inc., Pennsylvania, USA.

Werma, 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 ASAE, 28: 296–301.

Whitfield, D.E. (2000). Solar drying. International Conference on Solar Cooking, Kimberly, South Africa, 26th–29th November 2000.

Yagcioglu, A., Degirmencioglu, A. and Cagatay, F. (1999). Drying characteristics of laurel leaves under different conditions. Proceedings of the 7th International Congress on Agricultural Mechanization and Energy, 26–27 May, Adana, Turkey, pp. 565–569. Faculty of Agriculture, Çukurova University.

Yaldiz, O. and Ertekin, C. (2001). Thin layer solar drying of some vegetables. Drying Technology, 19: 583–596.

Zaman, M.A. and Bala, B.K. (1989). Thin layer solar drying of rough rice. Solar Energy, pp. 167–171.

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

APPENDICES

APPENDIX A: LIST OF TABLES

Table A1 Preliminary tests on temperatures developed in Sections A and B of the solar tent dryer on a typical day of November 2008

Time	T_a	Temperature (°C) at selected points in Section A				Temperature (°C) at selected points in Section B			
(hours)	(°C)	1	2	3	4	5	6	7	8
0	22.5	33.1	29.5	32.3	30.9	32.1	30.6	32.7	30.1
0.5	27.5	37.2	34.9	36.8	35.3	36.9	35.7	36.6	35.0
1	33.9	48.0	45.6	47.7	45.3	47.7	45.7	47.9	45.5
1.5	33.9	47.4	46.4	47.3	46.5	47.6	46.7	47.2	46.2
2	34.4	48.1	47.1	47.7	46.9	48.2	47.8	48.2	47.5
2.5	34.2	47.2	47.1	47.6	47.0	47.8	47.4	47.1	47.0
3	33.2	46.5	45.7	46.3	45.9	46.5	45.6	46.7	45.9
3.5	32.9	45.6	45.1	45.7	45.5	45.6	45.0	45.5	45.3
4	32.3	45.0	44.7	45.1	44.8	45.1	44.6	45.2	44.8
4.5	32.5	45.1	44.8	45.3	44.6	45.0	44.4	45.1	44.7
5	31.8	44.8	44.7	45.1	44.2	44.8	44.0	44.8	44.4
5.5	31.1	44.5	44.7	44.6	44.1	44.7	43.7	44.6	44.0
6	30.8	44.4	44.6	44.7	43.9	44.4	43.3	43.8	43.8
6.5	30.2	43.5	44.0	43.9	43.9	43.9	43.4	43.7	43.7
7	28.8	42.6	43.5	43.6	43.2	43.3	43.1	43.4	43.5
7.5	27.8	42.3	43.1	43.2	43.6	43.1	42.5	42.9	43.1
8	27.2	41.9	42.5	42.4	42.7	42.8	41.8	42.3	42.6

Table A2 Temperatures measured at different discrete points on Planes 1 and 2 in the solar tent dryer (17th November 2008)

Time	(a) Selected points at Plane 1									(b) Selected points at Plane 2								
(hours)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	28.1	28.5	29.2	28.8	29.1	30.1	29.4	28.9	29.3	29.9	30.2	29.6	30.4	30.2	29.5	29.7	30.1	29.3
2	29.2	29.5	30.1	28.9	29.8	30.2	30.1	30.4	30.2	30.8	31.9	30.3	31.1	30.8	30.9	30.3	31.2	30.6
3	30.5	31.1	30.4	30.4	31.3	31.4	31.1	31.5	30.8	31.5	32.1	30.5	32.3	30.9	32.1	30.6	32.7	31.8
4	31.9	32.2	31.7	32.1	32.4	32.5	32.9	32.2	32.1	35.3	36.2	34.9	36.8	35.3	36.9	35.7	36.6	35.0
5	43.7	43.8	43.2	42.9	44.1	44.0	43.9	43.8	44.2	45.5	46.1	45.6	47.7	45.3	47.7	45.7	47.9	45.5
6	46.2	45.9	46.3	45.9	46.8	46.5	46.5	46.9	46.6	47.1	47.4	46.4	47.3	46.5	47.6	46.7	47.2	46.2
7	46.1	46.1	45.9	45.8	46.0	45.5	45.4	45.5	46.1	46.6	46.5	45.7	46.3	45.9	46.5	45.6	46.7	45.9
8	44.9	44.6	44.7	43.8	44.4	43.7	43.3	44.2	44.7	45.5	45.6	45.1	45.7	45.5	45.6	45.0	45.5	45.3
9	43.6	43.3	42.9	43.4	43.1	42.7	42.7	43.4	43.3	44.7	45.0	44.7	45.1	44.8	45.1	44.6	45.2	44.8
10	42.1	42.4	42.5	43.1	42.7	41.9	42.2	43.1	42.8	44.1	44.2	43.8	43.9	44.1	44.4	43.7	43.8	43.8

Table A3 Temperatures measured at different discrete points on Planes 1 and 2 in the solar tent dryer (18th November 2008)

Time	(a) Selected points at Plane 1									(b) Selected points at Plane 2								
(hours)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	27.5	27.5	28.3	28.5	28.1	28.8	28.2	27.9	28.4	28.7	29.2	28.8	29.1	28.9	28.8	28.8	29.4	29.2
2	28.8	29.1	29.4	29.0	29.4	29.7	28.9	29.6	29.9	30.1	30.4	30.1	30.7	29.9	30.4	30.2	30.8	30.6
3	30.8	31.4	31.1	31.3	31.5	31.7	30.9	31.0	31.2	32.2	32.1	31.9	32.3	30.9	31.8	32.2	32.5	31.9
4	34.4	33.8	33.9	34.0	33.8	33.9	34.1	34.2	33.9	34.8	35.3	35.3	34.9	34.8	35.1	35.5	35.9	35.1
5	40.5	41.1	41.9	40.8	41.2	40.9	40.9	41.2	41.3	40.8	39.4	40.1	40.7	39.8	40.4	40.1	40.3	39.9
6	47.5	47.3	46.9	46.6	47.1	46.9	46.7	47.2	47.1	46.2	45.8	45.9	46.2	46.1	45.8	46.1	45.9	45.8
7	46.2	46.5	45.8	45.8	46.1	45.7	45.4	45.9	46.0	46.1	45.8	45.7	45.7	45.7	45.2	45.1	44.7	44.9
8	44.1	44.4	43.9	43.8	44.2	43.9	43.1	43.8	44.1	44.4	44.2	43.8	43.7	43.3	44.2	44.2	43.7	43.2
9	42.7	43.3	42.9	42.8	42.8	42.7	42.4	42.2	42.9	42.3	42.1	42.2	42.5	41.8	41.9	42.1	42.0	41.9
10	41.4	40.8	41.4	41.2	40.9	41.1	41.5	40.7	40.6	40.4	40.2	39.5	39.7	39.6	40.1	40.4	40.2	39.8

Table A4 Temperatures measured at different discrete points on Planes 1 and 2 in the solar tent dryer (19th November 2008)

Time	(a) Selected points on Plane 1									(b) Selected points on Plane 2								
(hours)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	27.8	28.2	28.1	27.9	27.5	28.4	28.3	28.0	27.7	28.9	28.6	28.8	28.7	29.1	28.9	28.8	29.0	29.1
2	29.1	29.0	28.9	29.1	29.1	28.9	28.8	29.3	29.2	30.8	30.4	29.9	30.0	30.7	30.7	30.2	29.9	30.1
3	30.8	31.2	30.9	31.3	30.8	30.8	30.9	31.2	30.9	31.3	32.2	31.6	31.7	31.8	32.1	31.5	31.3	31.6
4	31.6	31.4	31.7	31,8	32.2	32.2	32.3	31.9	31.7	32.5	32.4	33.3	32.9	33.1	32.9	32.8	33.2	32.2
5	38.8	39.3	39.5	38.7	39.7	38.6	38.8	39.6	39.1	40.3	40.5	40.3	40.3	40.4	39.8	40.3	40.0	39.9
6	44.6	45.5	45.2	44.8	45.9	45.1	44.8	44.9	44.9	45.5	45.2	45.6	45.3	44.9	44.9	45.1	45.3	45.4
7	45.7	46.0	45.9	45.8	46.6	45.9	45.7	46.0	45.8	46.9	46.5	46.7	46.3	46.6	46.5	46.0	46.2	46.3
8	44.6	45.6	45.1	44.3	44.2	43.9	44.1	43.9	44.1	45.7	45.6	45.5	45.7	46.1	45.6	45.8	46.2	45.5
9	42.1	42.4	42.1	41.9	42.6	42.2	41.8	42.7	41.8	43.5	42.8	43.1	43.3	43.3	43.2	42.8	42.9	43.4
10	40.2	39.7	40.1	40.4	39.9	40.3	40.4	39.5	39.7	41.7	41.3	40.5	40.6	41.1	41.4	40.9	40.8	41.2

Table A5 Temperature and relative humidity values during drying of amaranth grains in the model dryers and the open sun on typical day of December 2008

	Open sun (no cover)		**Yellow cover**		**Clear cover**		**Nectarine diffused cover**	
Time	**T_a (^oC)**	**Rh_a (%)**	**T_i (^oC)**	**Rh_i (%)**	**T_i (^oC)**	**Rh_i (%)**	**T_i (^oC)**	**Rh_i (%)**
9:00 a.m.	23.3	46	30.4	43	31.2	42	30.5	44
9:30 a.m.	24.8	40	33.2	34	34.8	33	33.2	35
10:00 a.m.	26.1	33	36.0	29	38.1	29	36.2	32
10:30 a.m.	28.3	32	39.2	28	41.3	27	38.9	31
11:00 a.m.	30.2	31	41.4	26	43.4	27	41.0	30
11:30 a.m.	30.4	30	43.8	25	46.5	26	43.2	30
12:00 p.m.	30.6	27	46.8	25	49.3	25	45.4	29
12:30 p.m.	31.0	26	47.7	24	49.5	23	45.8	28
1:00 p.m.	31.1	25	47.7	23	48.8	22	46.2	26
1:30 p.m.	32.1	25	48.1	20	49.2	20	46.5	24
2:00 p.m.	33.4	24	48.7	19	50.1	17	46.9	21
2:30 p.m.	33.5	24	49.1	20	50.7	15	47.9	20
3:00 p.m.	32.9	24	46.2	19	49.7	18	45.6	20
3:30 p.m.	32.5	25	43.4	20	46.6	19	42.6	21
4:00 p.m.	32.2	25	41.2	21	44.5	19	39.8	21
4:30 p.m.	30.8	26	39.1	22	42.8	20	37.6	22
5:00 p.m.	29.1	28	37.3	22	40.3	20	36.3	23

Table A6 Moisture content data for amaranth grains dried in the dryers with different cover materials and the open sun on a typical day of December 2008

	Yellow cover			Clear cover			Nectarine diffused cover			Open sun		
Time	**W_w (g)**	**W_d (g)**	**M (% d.b)**	**W_w (g)**	**W_d (g)**	**M (% d.b)**	**W_w (g)**	**W_d (g)**	**M (% d.b)**	**W_w (g)**	**W_d (g)**	**M (% d.b)**
9:00 a.m.	0.30	0.18	66.7	0.20	0.12	66.7	0.27	0.16	68.8	0.45	0.27	66.7
9:30 a.m.	0.34	0.23	47.8	0.23	0.16	43.8	0.26	0.17	52.9	0.48	0.31	54.8
10:00 a.m.	0.22	0.16	37.5	0.21	0.16	31.3	0.48	0.34	41.2	0.47	0.33	42.4
10:30 a.m.	0.38	0.30	26.7	0.39	0.32	21.9	0.37	0.28	32.1	0.35	0.26	34.6
11:00 a.m.	0.30	0.25	20.0	0.38	0.33	15.2	0.31	0.25	24.0	0.23	0.18	27.8
11:30 a.m.	0.33	0.29	13.8	0.39	0.35	11.4	0.47	0.40	17.5	0.28	0.23	21.7
12:00 p.m.	0.29	0.26	11.5	0.34	0.31	9.7	0.31	0.27	14.8	0.28	0.24	16.7
12:30 p.m.	0.31	0.28	10.7	0.24	0.22	9.1	0.27	0.24	12.5	0.24	0.21	14.3
1:00 p.m.	0.46	0.42	9.5	0.39	0.36	8.3	0.43	0.39	10.3	0.27	0.24	12.5
1:30 p.m.	0.64	0.59	8.5	0.45	0.42	7.1	0.36	0.33	9.1	0.62	0.56	10.7
2:00 p.m.	0.56	0.52	7.7	0.46	0.43	7.0	0.37	0.34	8.8	0.34	0.31	9.7
2:30 p.m.	0.44	0.41	7.3	0.34	0.32	6.3	0.39	0.36	8.3	0.36	0.33	9.1
3:00 p.m.	0.77	0.72	6.9	0.67	0.63	6.3	0.40	0.37	8.1	0.26	0.24	8.3
3:30 p.m.	0.62	0.58	6.9	0.48	0.45	6.7	0.42	0.39	7.7	0.42	0.39	7.7
4:00 p.m.	0.64	0.60	6.7	0.47	0.44	6.8	0.43	0.40	7.5	0.45	0.42	7.1
4:30 p.m.	0.48	0.45	6.7	0.49	0.46	6.5	0.45	0.42	7.1	0.46	0.43	7.0
5:00 p.m.	0.69	0.65	6.2	0.35	0.33	6.1	0.47	0.44	6.8	0.34	0.32	6.3

Table A7 Temperature and relative humidity values during drying of amaranth grains in the solar tent dryer and the open sun on a typical day of December 2008

Time	Open sun		Layer 1		Layer 2	
	T_a (°C)	Rh_a (%)	T_i (°C)	Rh_i (%)	T_i (°C)	Rh_i (%)
9:00 a.m.	22.6	45	31.3	36	38.3	36
9:30 a.m.	23.4	38	32.9	33	42.4	33
10:00 a.m.	25.2	33	35.8	30	45.2	30
10:30 a.m.	25.9	30	36.7	27	47.7	27
11:00 a.m.	26.2	28	38.8	24	49.7	24
11:30 a.m.	27.1	27	39.2	23	51.3	23
12:00 p.m.	27.7	26	40.2	22	52.4	22
12:30 p.m.	29.2	25	41.1	21	53.8	21
1:00 p.m.	30.4	26	43.2	22	54.7	22
1:30 p.m.	30.3	27	43.9	23	53.9	23
2:00 p.m.	30.1	27	42.9	24	52.6	24
2:30 p.m.	30.2	27	42.8	23	51.1	23
3:00 p.m.	30.1	27	42.8	24	49.2	24
3:30 p.m.	29.9	28	41.4	25	46.2	25
4:00 p.m.	28.7	29	40.1	27	44.3	27

Table A8 Moisture content data for amaranth grains dried in the actual solar tent dryer and the open sun on a typical day of December 2008

Time	Open sun			Layer 1			Layer 2		
	W_w (g)	W_d (g)	M (% d.b)	W_w (g)	W_d (g)	M (% d.b)	W_w (g)	W_d (g)	M (% d.b)
9:00 a.m.	0.45	0.27	66.7	0.41	0.25	64.0	0.5	0.31	61.3
9:30 a.m.	0.43	0.31	38.7	0.39	0.29	34.5	0.53	0.4	32.5
10:00 a.m.	0.19	0.15	26.7	0.42	0.34	23.5	0.29	0.24	20.8
10:30 a.m.	0.28	0.23	21.7	0.38	0.32	18.8	0.37	0.32	15.6
11:00 a.m.	0.27	0.23	17.4	0.40	0.35	14.3	0.37	0.33	12.1
11:30 a.m.	0.24	0.21	14.3	0.55	0.49	12.2	0.36	0.33	9.1
12:00 p.m.	0.27	0.24	12.5	0.77	0.70	10.0	0.55	0.51	7.8
12:30 p.m.	0.62	0.56	10.7	0.66	0.61	8.2	0.45	0.42	7.1
1:00 p.m.	0.34	0.31	9.7	0.42	0.39	7.7	0.47	0.44	6.8
1:30 p.m.	0.36	0.33	9.1	0.59	0.55	7.3	0.46	0.43	7.0
2:00 p.m.	0.26	0.24	8.3	0.46	0.43	7.0	0.48	0.45	6.7
2:30 p.m.	0.42	0.39	7.7	0.63	0.59	6.8	0.33	0.31	6.5
3:00 p.m.	0.46	0.43	7.0	0.65	0.61	6.6	0.34	0.32	6.3
3:30 p.m.	0.34	0.32	6.3	0.69	0.65	6.2	0.35	0.33	6.1
4:00 p.m.	0.35	0.33	6.1	0.70	0.66	6.1	0.35	0.33	6.1

Table A9 Variation of solar radiation parameters with time on 16th December 2008

Time	**Hour angle** ω **(degrees)**	**Beam radiation** I_b **(W/m²)**	**Diffuse radiation** I_d **(W/m²)**	**Total solar radiation** I_t **(W/m²)**	I_t **(kW/m²)**
9:00 a.m.	45	903.81	63.27	967.08	0.967
9:30 a.m.	37.5	1015.53	71.09	1086.62	1.087
10:00 a.m.	30	1109.52	77.67	1187.19	1.187
10:30 a.m.	22.5	1184.47	82.91	1267.39	1.267
11:00 a.m.	15	1238.85	86.72	1325.57	1.326
11:30 a.m.	7.5	1271.78	89.02	1360.80	1.361
12:00 p.m.	0	1282.99	89.81	1372.80	1.373
12:30 p.m.	-7.5	1271.86	89.03	1360.89	1.361
1:00 p.m.	-15	1238.85	86.72	1325.57	1.326
1:30 p.m.	-22.5	1184.47	82.91	1267.39	1.267
2:00 p.m.	-30	1109.52	77.67	1187.19	1.187
2:30 p.m.	-37.5	1015.53	71.09	1086.62	1.087
3:00 p.m.	-45	903.81	63.27	967.08	0.967
3:30 p.m.	-52.5	776.56	54.36	830.92	0.831
4:00 p.m.	-60	635.71	44.50	680.21	0.680

Table A10 Variation of solar radiation parameters with time on 18th December 2008

Time	Hour angle ω (degrees)	Beam radiation I_b (W/m^2)	Diffuse radiation I_d (W/m^2)	Total solar radiation I_t (W/m^2)	Total solar radiation I_t (kW/m^2)
9:00 a.m.	45	903.73	63.26	966.99	0.967
9:30 a.m.	37.5	1015.44	71.08	1086.52	1.087
10:00 a.m.	30	1109.42	77.66	1187.08	1.187
10:30 a.m.	22.5	1184.37	82.91	1267.27	1.267
11:00 a.m.	15	1238.74	86.71	1325.45	1.325
11:30 a.m.	7.5	1271.67	89.02	1360.68	1.361
12:00 p.m.	0	1282.88	89.80	1372.68	1.373
12:30 p.m.	-7.5	1271.74	89.02	1360.77	1.361
1:00 p.m.	-15	1238.74	86.71	1325.45	1.325
1:30 p.m.	-22.5	1184.37	82.91	1267.27	1.267
2:00 p.m.	-30	1109.42	77.66	1187.08	1.187
2:30 p.m.	-37.5	1015.44	71.08	1086.52	1.087
3:00 p.m.	-45	903.73	63.26	966.99	0.967
3:30 p.m.	-52.5	776.49	54.35	830.84	0.831
4:00 p.m.	-60	635.65	44.50	680.15	0.680
4:30 p.m.	-67.5	903.73	63.26	966.99	0.967
5:00 p.m.	-75	1015.44	71.08	1086.52	1.087

Table A11 Absolute residual errors (%) for moisture ratio of amaranth grains dried in the open sun (no cover material)

Drying time (hours)	Thin layer drying models					
	Newton	**Page**	**Modified Page**	**Henderson & Pabis**	**Logarithmic**	**Wang & Singh**
0	0.1	0.1	0.1	27.7	3.8	10.6
0.5	2.3	1.1	11.9	28.7	7.5	7.9
1	2.0	2.1	13.4	24.7	5.0	0.6
1.5	1.8	0.1	17.3	23.8	6.9	0.3
2	4.1	0.2	17.8	20.8	6.6	1.1
2.5	10.4	3.3	14.4	14.5	3.1	2.4
3	20.9	10.5	6.9	4.6	3.7	3.6
3.5	19.9	7.5	7.4	3.3	0.4	8.3
4	18.2	4.4	7.8	2.6	3.6	22.0
4.5	20.7	5.6	4.3	1.7	4.1	32.5
5	18.7	3.5	3.9	2.3	8.1	42.8
5.5	14.0	0.5	5.6	0.3	13.9	48.7
6	13.7	0.1	3.6	2.0	16.1	44.5
6.5	14.2	1.2	0.9	4.3	17.5	29.8
7	15.4	3.5	2.4	7.1	18.2	2.0
7.5	12.1	1.8	1.4	5.4	21.8	35.1
8	19.8	10.2	10.3	14.0	17.6	102.9
Mean	12.3	3.3	7.6	11.1	9.3	23.2
Stdev	7.5	3.4	5.7	10.3	6.7	26.8
η_p(%)	29.4	88.2	64.7	58.8	64.7	47.1

η_p = percentage of predicted data that lie within a ± 10% residual error interval

stdev = standard deviation

Table A12 Absolute residual errors (%) for moisture ratio of amaranth grains dried in the model dryer with nectarine diffused cover

Drying time (hours)	Thin layer drying models					
	Newton	Page	Modified Page	Henderson & Pabis	Logarithmic	Wang & Singh
0	0.1	0.1	0.1	27.2	3.8	10.4
0.5	4.8	4.7	5.3	23.0	0.7	1.1
1	9.3	5.9	6.8	18.6	2.0	6.7
1.5	14.7	5.1	6.2	13.3	5.2	13.1
2	26.9	2.2	1.2	2.4	14.3	23.4
2.5	45.5	15.0	14.3	14.1	28.5	35.4
3	45.5	13.9	13.8	16.4	25.8	25.8
3.5	48.0	15.6	16.3	21.0	25.2	15.2
4	57.0	23.1	24.8	31.3	30.0	7.3
4.5	56.5	23.7	26.6	33.9	26.9	7.1
5	44.7	15.6	19.5	26.4	14.9	23.8
5.5	39.4	12.9	17.7	24.3	8.6	29.9
6	32.3	8.6	14.2	20.1	1.2	28.5
6.5	30.3	8.5	15.0	20.2	1.9	14.4
7	26.3	6.5	13.7	18.2	6.2	9.5
7.5	26.6	8.1	16.0	20.0	7.0	49.4
8	27.7	10.2	18.8	22.3	7.1	104.9
Mean	31.5	10.6	13.5	20.8	12.3	23.9
Stdev	17.2	6.7	7.5	7.3	10.8	24.3
η_p(%)	17.6	52.9	29.4	5.9	58.8	29.4

η_p = percentage of predicted data that lie within a ±10% residual error interval

stdev = standard deviation

Table A13 Absolute residual errors (%) for moisture ratio of amaranth grains dried in the model dryer with yellow cover

Drying time (hours)	Thin layer drying models					
	Newton	**Page**	**Modified Page**	**Henderson & Pabis**	**Logarithmic**	**Wang & Singh**
0	0.1	0.1	0.1	23.8	3.3	14.7
0.5	6.2	2.1	2.7	18.3	1.5	0.0
1	4.2	8.1	9.1	18.9	1.7	5.5
1.5	14.1	2.1	3.6	9.8	6.1	20.7
2	20.3	1.6	0.2	3.2	10.1	28.2
2.5	40.4	18.0	15.7	15.3	26.4	44.6
3	37.8	16.4	14.0	15.7	21.9	30.7
3.5	24.6	6.4	4.3	7.0	8.3	3.2
4	20.4	4.5	2.6	5.9	2.9	17.4
4.5	19.0	5.2	3.4	6.9	0.0	34.8
5	17.8	6.2	4.7	8.0	2.5	47.6
5.5	13.6	4.3	3.0	6.0	7.2	54.0
6	11.7	4.3	3.2	5.8	9.7	48.9
6.5	6.5	0.9	0.1	2.2	14.6	33.7
7	5.7	1.3	0.6	2.3	15.8	3.5
7.5	2.3	0.9	1.4	0.1	18.9	37.1
8	8.2	5.6	5.1	6.2	14.6	106.1
Mean	14.9	5.2	4.3	9.2	9.7	31.2
Stdev	11.6	5.1	4.6	6.8	7.9	25.9
η_p(%)	41.2	88.2	88.2	70.6	58.8	23.5

η_p = percentage of predicted data that lie within a ±10% residual error interval

stdev = standard deviation

Table A14 Absolute residual errors (%) for moisture ratio of amaranth grains dried in the model dryer with clear cover

Drying time (hours)	**Thin layer drying models**					
	Newton	**Page**	**Modified Page**	**Henderson & Pabis**	**Logarithmic**	**Wang & Singh**
0	0.0	0.1	0.0	37.3	8.3	20.3
0.5	13.8	1.1	8.5	27.3	3.2	1.0
1	20.3	2.1	5.6	21.2	7.7	15.5
1.5	31.6	0.1	6.3	11.2	16.0	32.1
2	48.1	0.2	11.3	3.5	27.9	48.7
2.5	56.2	3.3	11.8	13.6	31.8	49.0
3	50.4	10.5	5.3	14.1	23.5	28.0
3.5	33.8	7.5	5.7	6.0	6.7	5.5
4	25.4	4.4	9.2	3.5	3.0	32.1
4.5	28.9	5.6	2.7	10.5	3.2	49.9
5	19.2	3.5	5.8	5.6	13.0	66.2
5.5	22.7	0.5	1.5	11.7	12.6	68.1
6	13.5	0.1	2.2	5.7	20.9	60.9
6.5	3.0	1.2	8.1	2.3	29.4	42.6
7	2.8	3.5	10.9	6.6	34.3	11.6
7.5	1.1	1.8	7.3	3.9	33.9	39.2
8	5.4	10.2	0.4	3.2	30.1	116.5
Mean	22.1	3.3	6.0	11.0	18.0	40.4
Stdev	17.7	3.4	3.7	9.6	11.6	28.3
η_p(%)	29.4	88.2	82.4	52.9	35.3	11.8

η_p = percentage of predicted data that lie within a ±10% residual error interval

stdev = standard deviation

Table A15 Absolute residual errors (%) for moisture ratio of amaranth grains dried under the open sun

Drying time (hours)	Thin layer drying models					
	Newton	Page	Modified Page	Henderson & Pabis	Logarithmic	Wang & Singh
0	0.1	0.1	0.1	2.2	20.2	21.8
0.5	21.7	4.9	4.8	24.2	0.9	11.5
1	27.0	7.3	7.2	29.5	6.2	31.6
1.5	14.5	1.6	1.8	16.6	1.0	28.7
2	8.3	3.8	4.0	10.0	2.8	25.3
2.5	3.0	4.7	4.9	4.4	3.5	15.7
3	4.5	8.1	8.3	3.4	6.6	2.2
3.5	6.2	6.7	6.9	5.4	4.4	17.4
4	9.3	7.6	7.8	8.7	4.2	33.7
4.5	13.0	9.9	10.1	12.5	5.3	45.9
5	12.1	8.3	8.4	11.8	2.0	47.7
5.5	9.9	5.8	5.9	9.7	2.3	38.4
6	4.5	0.3	0.4	4.3	9.8	13.3
6.5	3.7	7.9	7.8	3.8	20.4	32.9
7	4.9	8.7	8.6	5.0	22.6	89.7
Mean	9.5	5.7	5.8	10.1	7.5	30.4
Stdev	7.3	3.1	3.1	8.0	7.4	20.8
η_p(%)	40.0	40.0	40.0	40.0	53.3	6.7

η_p = percentage of predicted data that lie within a ±5% residual error interval

stdev = standard deviation

Table A16 Absolute residual errors (%) for moisture ratio of amaranth grains dried in the solar tent dryer (Layer 1)

Drying time (hours)	Thin layer drying models					
	Newton	Page	Modified Page	Henderson & Pabis	Logarithmic	Wang & Singh
0	0.0	0.0	0.0	17.1	23.6	23.8
0.5	28.3	5.1	6.6	7.4	0.7	15.6
1	32.8	3.9	6.2	12.5	4.8	35.6
1.5	20.9	5.2	2.6	4.2	2.0	32.9
2	19.1	3.8	1.0	4.6	0.3	32.2
2.5	8.6	8.6	5.9	2.6	5.7	12.9
3	8.4	4.5	2.0	0.6	2.2	2.7
3.5	12.5	3.2	5.7	5.3	5.1	19.5
4	6.1	0.5	2.5	1.0	2.1	42.4
4.5	2.5	0.5	1.2	1.0	1.1	55.5
5	0.3	1.1	0.2	2.2	0.8	57.0
5.5	1.3	1.7	0.7	3.0	0.5	45.0
6	1.1	0.8	0.0	2.2	1.8	17.2
6.5	3.3	3.8	4.5	2.5	7.0	31.5
7	3.4	4.1	4.6	2.9	7.6	93.4
Mean	9.9	3.1	2.9	4.6	4.4	34.5
Stdev	10.6	2.3	2.4	4.6	5.9	22.5
η_p(%)	46.7	80.0	73.3	73.3	66.7	6.7

η_p = percentage of predicted data that lie within a ±5% residual error interval

stdev = standard deviation

Table A17 Absolute residual errors (%) for moisture ratio of amaranth grains dried in the solar tent dryer (Layer 2)

Drying time (hours)	**Thin layer drying models**					
	Newton	**Page**	**Modified Page**	**Henderson & Pabis**	**Logarithmic**	**Wang & Singh**
0	0.0	0.0	0.0	33.0	24.1	25.2
0.5	28.1	0.3	3.1	12.0	1.8	14.2
1	39.0	1.7	6.1	1.2	8.6	40.9
1.5	33.2	3.1	1.8	1.3	7.0	44.3
2	28.4	3.7	1.4	0.2	6.9	38.0
2.5	34.1	5.8	10.9	9.6	16.1	30.6
3	27.8	6.5	11.0	9.4	15.2	2.0
3.5	20.7	5.9	9.5	7.8	12.9	28.6
4	13.3	3.5	6.4	4.6	9.3	53.5
4.5	2.4	3.5	1.4	3.1	1.1	68.1
5	1.6	2.1	0.6	2.1	2.1	66.3
5.5	1.3	1.0	0.2	1.2	3.0	49.6
6	2.1	0.7	1.6	0.4	4.8	16.4
6.5	3.6	2.8	3.5	2.5	7.0	34.9
7	2.6	2.1	2.6	1.9	6.3	99.7
Mean	15.9	2.9	4.0	6.0	8.4	40.8
Stdev	14.7	2.0	3.8	8.4	6.3	24.6
η_p(%)	46.7	80.0	66.7	66.7	33.3	6.7

η_p = percentage of predicted data that lie within a ±5% residual error interval

stdev = standard deviation

Table A18 Colour, hardness and crude protein content of amaranth grains dried under different cover materials and the open sun

	Colour parameters for amaranth grains				Hardness	Crude protein (CP) content	
Type of cover material	***L****	***a****	***b****	***h****	**(kg)**	**%N**	**CP (%)**
Yellow cover	53.51	7.55	40.43	79.42	2.0	2.73	17.06
	51.99	7.87	38.84	78.55	2.3	2.70	16.88
	53.73	7.56	37.64	78.64	2.0	2.77	17.31
	53.50	7.45	40.32	79.53	2.2	2.73	17.06
	52.01	7.82	38.83	78.61	2.3	2.71	16.94
	52.22	7.81	39.79	78.90	2.1	2.76	17.25
Clear cover	53.63	7.58	38.98	79.00	2.1	2.75	17.19
	54.84	6.80	34.91	78.98	2.2	2.71	16.94
	54.40	7.07	36.87	79.15	2.1	2.74	17.13
	54.84	6.85	36.97	79.50	2.3	2.74	17.13
	53.62	7.57	39.67	79.20	2.4	2.73	17.06
	53.59	7.56	38.85	79.07	2.1	2.72	17.00
Nectarine diffused cover	53.31	6.77	38.09	79.92	2.4	2.80	17.50
	54.67	7.25	35.40	78.43	2.1	2.73	17.06
	51.85	8.10	37.50	77.81	2.3	2.72	17.00
	53.50	7.43	37.77	78.87	2.1	2.73	17.06
	53.30	7.12	37.78	79.33	2.3	2.78	17.38
	53.45	7.22	37.89	79.21	2.2	2.76	17.25
No cover (open sun)	54.76	7.12	37.15	79.15	2.2	2.90	18.13
	54.34	7.21	36.43	78.81	2.0	2.77	17.31
	54.24	7.54	35.96	78.16	2.4	2.81	17.56
	53.92	7.34	36.36	78.59	2.3	2.77	17.31
	53.87	7.11	36.96	79.11	2.4	2.78	17.38
	54.05	7.19	36.56	78.87	2.1	2.81	17.56

APPENDIX B: LIST OF FIGURES

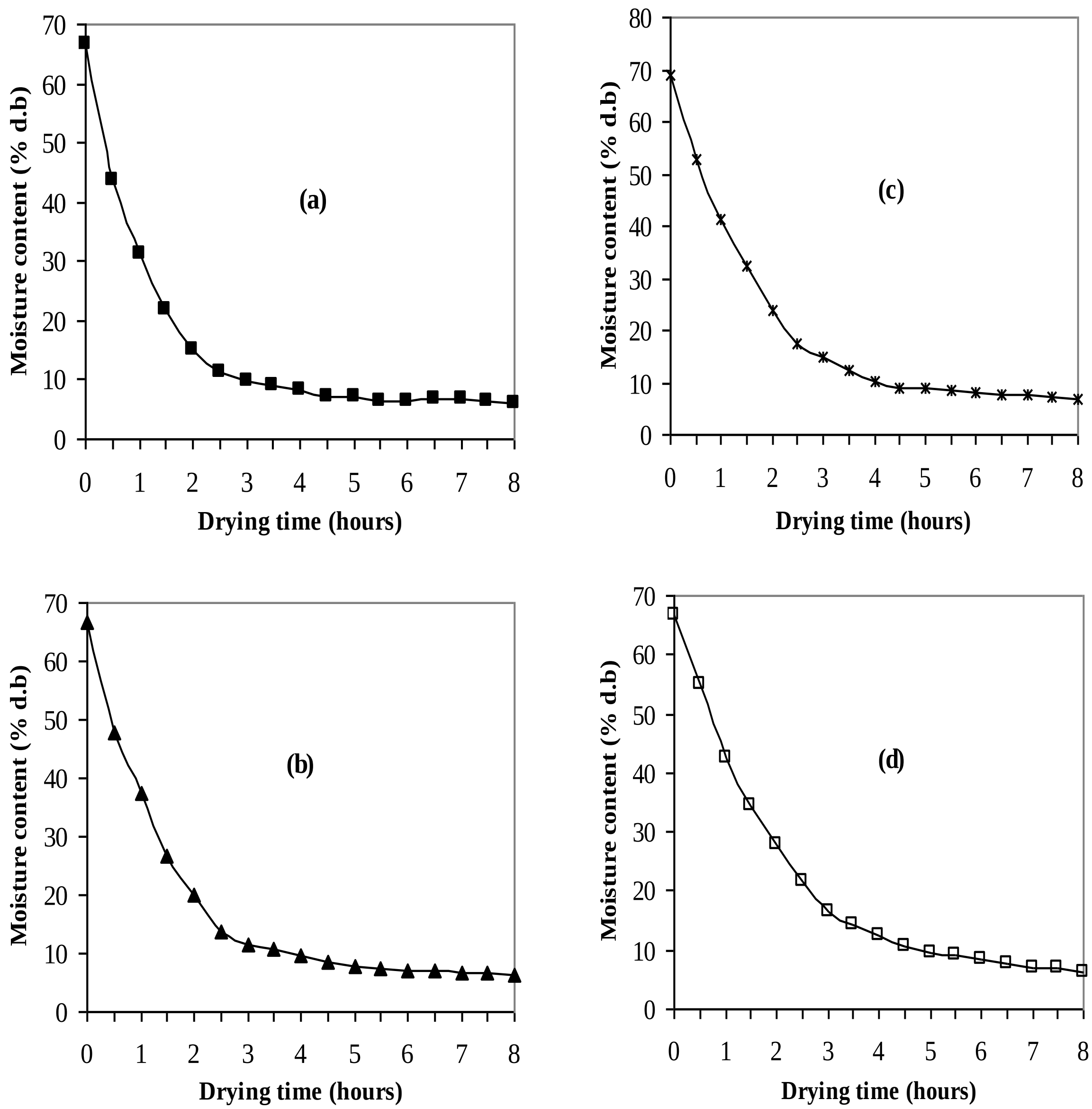

Figure B1 Drying curves for comparing thin layer drying of amaranth grains under the model dryers with clear (a), yellow (b) and nectarine diffused (c) cover materials, and the open sun (d).

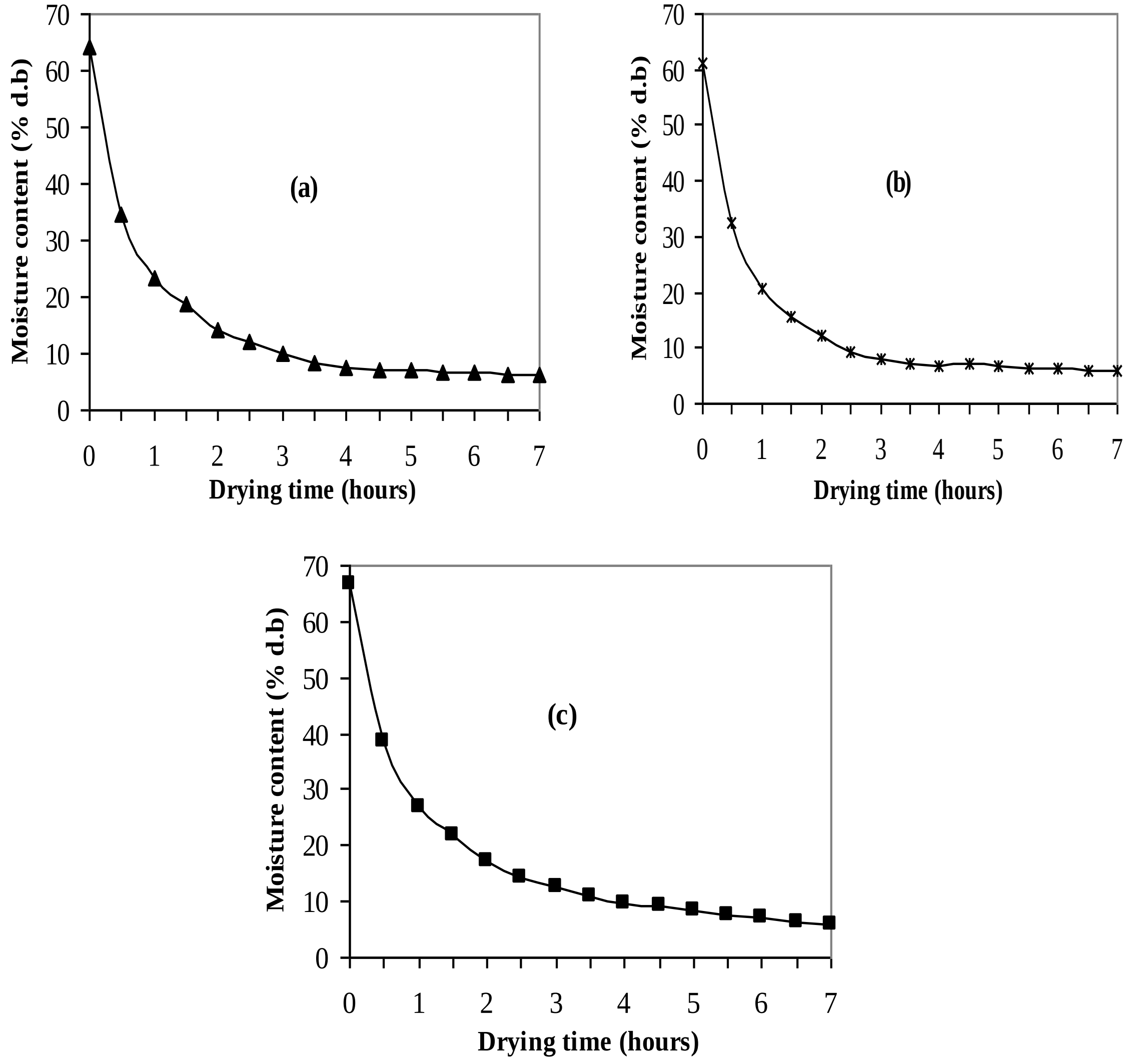

Figure B2 Drying curves for comparing thin layer drying of amaranth grains in Layers 1 (a) and 2 (b) of the solar tent dryer, and the open sun (c).

APPENDIX C: LIST OF PLATES

Plate C1 Amaranth plants after 30 days from planting date.

Plate C2 Amaranth plants after 60 days from planting date.

Plate C3 Amaranth plants after 75 days from planting date.

Plate C4 Amaranth plants after 90 days from planting date.

Plate C5 Development of the model solar tent dryer.

Plate C6 Developed model solar tent dryers with nectarine diffused, clear and yellow PVC cover materials.

Plate C7 The actual solar tent dryer under natural convection.

PUBLICATIONS

JOURNALS

Ronoh, E.K., Kanali, C.L., Mailutha, J.T. and Shitanda, D. (2010). Thin layer drying kinetics of amaranth (*Amaranthus cruentus*) grains in a natural convection solar tent dryer. African Journal of Food, Agriculture, Nutrition and Development (AJFAND), 10(3): 2218–2234.

Ronoh, E.K., Kanali, C.L., Mailutha, J.T. and Shitanda, D. (2009). Modeling thin layer drying of amaranth seeds under open sun and natural convection solar tent dryer. Agricultural Engineering International: the CIGR EJournal. Manuscript 1420. Vol. XI. November, 2009.

CONFERENCE PROCEEDINGS

Ronoh, E.K., Kanali, C.L., Mailutha, J.T. and Shitanda, D. (2010). Analysis of thin layer solar drying characteristics and product quality of amaranth grains. Proceedings of the 2010 Sustainable Research and Innovation Conference, Department of Mechanical Engineering, Jomo Kenyatta University of Agriculture and Technology. African Institute for Capacity Development (AICAD), Kenya. 8th–9th April 2010. ISSN: 2073–5812, Vol. II.

Ronoh, E.K., Kanali, C.L., Mailutha, J.T. and Shitanda, D. (2009). Modeling thin layer drying of amaranth seeds under open sun and natural convection solar tent dryer. Proceedings of Mechanical Engineering Annual Seminar – Series 11, Jomo Kenyatta University of Agriculture and Technology, Kenya. 2nd–3rd April 2009. ISSN: 2073–5812, pp. 23–28.

POSTERS

Ronoh, E.K., Kanali, C.L., Mailutha, J.T. and Shitanda, D. (2009). Thin layer drying characteristics of amaranth grains under the open sun and in a natural convection solar tent dryer. 6th Global Consortium of Higher Education and Research for Agriculture (GCHERA) Conference. 23rd–27th November 2009, Nairobi, Kenya.