CHARACTERISING THIN LAYER DRYING OF HIGH MOISTURE CONTENT VEGETABLES IN A SOLAR TUNNEL DRYER

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Characterising Thin Layer Drying of High Moisture Content Vegetables in a Solar Tunnel Dryer

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DECLARATION

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

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DEDICATION

To my family for their support during my study. I wish you all God’s blessings for walking this journey with me.

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ABBREAVIATIONS AND NOTATIONS

AOAC	Association of Official Analytical Chemists
ASAL	Arid and Semi-Arid Lands
b*	Colour parameter, blue-yellow spectrum
C_{pa}	Specific heat capacity of air (J/kg-K)
CSD	Conventional sun drying
db	Dry basis (%)
DCPIP	Dichlorophenolindophenol
D_{eff}	Effective moisture diffusivity (m^2s-1)
FAO	United Nations Food and Agriculture Organization
H	Humidity ratio of air (kg water/kg dry air)
h*	Hue angle (degrees)
h_{fg}	Latent heat of vaporization (kJkg−1)
I	Solar intensity in (w/m^2)
IPAR	Institute of Policy Analysis and Research
IPGRI	International Plant Genetic Resources Institute
k	Drying rate constant (h^{-1})
L*	Colour parameter, light-dark spectrum
M	Moisture content at time t hours (% dry basis)
M_a	Mass flow rate of air (kg/s)
MAPS	Medicinal and Aromatic Plants
Me	Equilibrium moisture content (% dry basis)
Mo	Initial moisture content (% dry basis)

MR	Moisture ratio, dimensionless
$\mathbf{MR_{act,i}}$	Actual moisture ratio
$\mathbf{MR_{pre,i}}$	Predicted moisture ratio
MWD	Microwave drying
N	Number of observations
Nc	Number of correctly predicted data observations
Nt	Number of trial data observations
NASA	National Aeronautics and Space Administration
OS	Open sun
$\mathbf{Q_i}$	Heat energy incident on the collector surface (W)
Q_u	Useful heat gain (W)
$\mathbf{R^2}$	Coefficient of determination
RDA	Recommended Dietary Allowance
RH	Relative Humidity (%)
$\mathbf{Rh_{amb}}$	Relative humidity in the open sun (%)
$\mathbf{Rh_{in}}$	Relative humidity in the dryer chamber inlet (%)
RMSE	Root mean square error
S	Slope
SD	Solar dryer
S.R	Solar radiation (W/m^2)
t	Drying time (hours)
$\mathbf{T_{amb}}$	Ambient temperature (^{o}C)
$\mathbf{T_{in}}$	Temperature developed inlet to drying chamber (^{o}C)

TLD	Thin Layer Drying
$\mathbf{T_{out}}$	Temperature at exit of drying chamber (^{o}C)
VE	Vitamin C equivalent (mg/ml)
WRAP	Waste & Resources Action Program
$\boldsymbol{\beta}$	Beta carotene level (mg/100g)
$\boldsymbol{\varepsilon}$	Absolute residual error (%)
$\boldsymbol{\eta_c}$	Collector efficiency (%)
$\boldsymbol{\chi^2}$	Reduced chi-square
$\dot{m}$	Mass flow rate of air (kg/s)
$\mathbf{A_c}$	Collector area (m^2)
a*	Colour parameter, green-red spectrum
a,b,c,n,k	Coefficients in drying models
n	Positive integer

ABSTRACT

The post-harvest losses experienced by high moisture content vegetables form the bulk of most of the postharvest losses, estimated to be 30-40% in the developing countries in the tropics and subtropics. This study involved thin layer drying of five high moisture content vegetables (kales, cabbage, cowpeas, amaranth and stinging nettle) in a solar tunnel dryer and the open sun, while monitoring the temperature, relative humidity and solar insolation on the solar tunnel dryer and then evaluating drying characteristics, effect of drying on colour, ascorbic acid and beta carotene retention of the dried vegetables. The vegetables dried from an initial moisture content of 1288.9, 669.2, 474.7, 566.7, and 566.7% dry basis for cabbages, kales, cowpeas, amaranth and stinging nettle, respectively, to stable moisture content of less than 12% dry basis within 8 hours except cabbages which took 30 hours. Hue angles for the dried vegetables (127.9, 81.92, 107.01, and 109.370) for kales, cabbage, amaranth and stinging nettle, respectively, were higher than those corresponding to open sun drying (118.7, 77.25, 96.61, and 102.02^0). Ascorbic level dropped significantly for both drying methods compared to the fresh ones. However, beta carotene retention in all the vegetables were higher for the solar tunnel drying than the open sun. Results of temperature and relative humidity analysis showed that there was significant difference in temperature and relative humidity in the collector, dryer and the open sun ($P<0.05$). The Page model best described the drying of kales, cabbage, cowpeas and amaranth with R^2 values of 0.985-0.989, $\chi^2 = 0.00145-0.00220$, RMSE = 0.03850-0.04559 and $\varepsilon(\%) = 7.9\pm11.9-27.3\pm34.6$, respectively, in the solar tunnel dryer. In addition, the Verma *et al* model was best in characterising thin layer drying of stinging nettle ($R^2 = 0.994$, $\chi^2 = 0.00112$ and RMSE = 0.02899 and $\varepsilon(\%) = 11.9 \pm 19.1$) in the solar tunnel dryer. The results therefore demonstrate that the solar tunnel dryer can be utilized in drying high moisture content vegetables without adversely affecting the colour and nutritive properties of the vegetables. The solar dryer can therefore provide easy and applicable solution to the post-harvest losses of high moisture content vegetables especially to small scale farmers in rural areas while utilising environmentally friendly and abundantly available free solar energy.

CHAPTER ONE

INTRODUCTION

1.1 Background to the Study

The horticulture sub-sector in Kenya comprises of five commodities namely vegetables, flowers, fruits, and nuts, medicinal and aromatic plants (MAPS). Of the total value of horticultural produce, vegetables account for 44.6%, fruits 29.6%, flowers 20.3%, and nuts, medicinal and aromatic plants account for the rest. About 95% of horticultural production goes to the domestic market and 5% to the export market. (National horticulture policy, 2012).The vegetable sub-sector is important in attaining food security and improving livelihood for smallholder farmers who produce 100% of African vegetables and up to 70% of the Exotic and Asian vegetables (National horticulture policy, 2012).

The main vegetable crops grown by smallholder farmers for both subsistence and commercial purposes in Kenya include cabbages, tomatoes, kales (sukuma wiki), onions and indigenous vegetables commonly referred to as African Leafy Vegetables (ALVs) such as amaranth, stinging nettle, black night shade etc. (Omiti, Omolo, & Manyengo*,* 2004). In addition, high moisture leafy vegetables are mainstays in the diets of rural and urban households across Kenya and therefore play a major role in food security as well as an important source of income. Further, these vegetables have high moisture content which ranges between 80-95% (Bogert, George, & Howes, 2000; Emebu & Anyika, 2011). As such, post-harvest losses in the vegetables are estimated at 40% (National horticulture policy, 2012), partly due to the high moisture content which encourages micro-organisms and enzymatic activity. The other major cause of spoilage is the poor post-harvest handling, poor preservation methods and inadequate and inappropriate storage practices. Therefore, it is necessary to adopt technologies which can effectively reduce the spoilage by applying appropriate method of post-harvest handling, processing and preservation. Some of these preservation methods that have been used include pre cooling using water, room cooling, forced air-cooling, and vacuum cooling after harvesting. However, due to their energy requirement, the technologies are not suitable and affordable to most farmers since there are mainly in areas without national grid connection.

Drying has been traditionally used to preserve vegetables by extending their storage life well beyond few weeks and making them available off-season. Drying converts the vegetables into lightweight, easily transportable, and storable product. An advantage of this method is that the vegetable is easily convertible into fresh like form by rehydrating it and used throughout the year. In addition to availability all-round the year for consumption, reducing losses, labour and storage space, dehydrated vegetables are simple to use and have longer shelf life than fresh vegetables (Chauhan & Sharma, 1993) as well as concentration of nutrients. Various traditional drying methods practised overtime include, open sun drying, drying in the shade and solar drying. Open sun drying is a conventional heating method where transfer of thermal energy from the product surface towards their centre is slow. The method also exposes the product to contamination by dirt, dust as well as by bacteria (Hii, Jangam, Ong & Mujumdar, 2012). Its labour intensive, not possible during rainy days or at night and can lead to excessive respiration and fungal growth hence vegetable losses and yellowing. However, sun drying cannot be utilised throughout the year especially during the rainy and cold season. Shade drying is also a common practise used for drying vegetables in the rural areas. However, it has limitations during rainy days if the product is under trees and at night due to low temperatures and infestation by rodents and other insects. The product is also prone to contamination either by animals or birds droppings and introduction of foreign material like dust and fungal growth due to its slow process thus leading to high losses. Shade drying though maintains better quality but takes many days to dry the product to constant weight and attain the desired safe moisture content. While fossil fuel provide about 90% of the total world energy, (Idiata, Olubodun, & Ukponmwan, 2008); the burning of fossil based fuel causes some of environmental problems like materials and properties corrosion, acid rains, visibility problems, greenhouse and ozone layer depletion (global warming). Solar energy therefore comes forms one of the most promising renewable energy sources in the world because of its abundance, inexhaustible and non-pollutant in nature compared with higher prices and shortage of fossil fuels (Basunia & Abe, 2001). For the purpose of this study, solar energy was used as the main source of energy for the preservation of high moisture content vegetables through drying.

Drying of vegetables using solar drying systems offer alternative methods to open sun drying and hence improve on the quality of the final product, as well as increasing the shelf life. Solar dryers are some of the systems used and they protect vegetables from possible contaminants, while providing improved conducive environment which results in high drying rates, better than open sun drying and shade drying (Bala & Mondol, 2001). Solar dryers can easily be adopted due to local availability of the construction materials and simple designs thus offering effective drying technology alternatives for preservation of vegetables, which is environmentally friendly (Jairaj, Singh & Srikant, 2009; Perumal, 2007). This technology is suitable for use in most rural areas in Kenya as there is abundant supply of sunshine (Rabah, 2005). Further, most of these regions are not supplied with electricity and where connected, it's too costly to run drying systems and hence, beyond the reach of most farmers who would be in need of value addition and preservation methods like drying of vegetables. Poverty levels also prohibit the use fossil fuels for drying of agricultural produce due to the cost of procuring the same.

Solar drying methods are usually classified into four categories according to the mechanism by which the energy used to remove moisture, is transferred to the product (Furlan, Mancini, & Sayigh, 1983). These mechanisms are open sun dryers, direct solar dryer, indirect solar dryer and mixed-type solar dryers. Open sun drying involves placing material to be dried directly under hostile climate conditions like solar radiation, ambient air temperature, relative humidity, and wind speed to achieve drying. In direct solar dryers, the material to be dried is placed in an enclosure, with transparent covers or side panels. Heat is generated by absorption of solar radiation on the product itself as well as the internal surfaces of the drying chamber. This heat evaporates the moisture from the drying product and promotes the natural circulation of drying air. For indirect solar dryers, air is first heated in a solar air heater and then ducted to the drying chamber. Mixed-type solar dryers combine action of the solar radiation incident directly on the material to be dried and the air pre-heated in the solar air heater furnishes the energy required for the drying process. Hybrid systems are usually designed with a specific product in mind and may include combination of more than one form of energy (Sharma, Chen & Lan, 2009).

A variety of solar drying technologies and designs such as box, tent and greenhouse dryers have been in use in Kenya for drying of agricultural produce (Kerr, 1998). These systems can be applied for drying of high moisture content vegetables in Kenya since there is abundance of solar energy. However, not much have been done on use of solar tunnel dryer in drying high moisture content vegetables in Kenya.

Thin layer drying (TLD) 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, Yadollahinia, & Rafiee, 2006). It normally forms the basis of understanding the drying characteristics of food materials since every material is unique (Mwithiga & Olwal, 2005). Drying of moist materials is a complicated process involving simultaneous, coupled heat and mass transfer phenomena, which occur inside the material being dried (Yilbas, Hussain & Dincer, 2003). Drying rate is controlled by the external factors of the process and the internal diffusion mechanisms. Apart from the external factors, the type and size of the product also affect the drying rate. Thus many products, i.e. fruits and vegetables, sliced fruits, are better dried in thin layers.

Thin layer drying (TLD) models fall under three categories namely, theoretical, semi-theoretical and empirical. They contribute to the understanding of the characteristics of drying agricultural products. Empirical models are important not only in describing thin layer water removal, but also in describing heat penetration during this removal when hot air is used. In this case, heating is governed by the diffusion Equation, that involves the drying rate in the energy balance (Karim & Hawlader, 2005), Mariani, Lima and Coelho, 2008), and this rate can be determined by an empirical model. 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. Examples of semi-empirical models are the Newton model, Page model, Modified Page model, Henderson and Pabis model and Logarithmic model.

Among these models, the theoretical approaches account for only the internal resistance to moisture transfer, while semi-theoretical and empirical approaches consider only the external resistance to moisture transfer between the product and the air (Usub, Lertsatitthankorn, Poomsa-ad, Wiset, & Soponronnarit, 2010). In the development of TLD models for agricultural products, moisture content of the material at any time after it has been subjected to a constant relative humidity and temperature is measured and correlated to the drying parameters (Midilli, Kucuk & Yapar, 2002); Togrul & Pehlivan, 2004). Thin layer drying models provide valuable tools 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 & Abe, (2001).

This study focused on determining the efficacy of the models discussed above in the analysis of thin layer drying of high moisture content vegetables in a solar tunnel 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. Whereas some studies have been done on modelling of the thin layer drying process of some high moisture vegetables, solar tunnel drying studies are lacking hence the purpose of this study.

1.2 Statement of the Problem

Leafy high moisture vegetables, both exotic and indigenous are produced in abundance in almost all agro-ecological zones of Kenya during the rainy seasons, and this leads to over supply during that period. The oversupply results in large quantities of vegetables going to waste due to lack of appropriate preservation technologies. The losses experienced by high moisture content vegetables form the bulk of most of the postharvest losses, estimated to be 30-40% in the developing countries in the tropics and subtropics (Salunkhe & Desai, 1984). Preservation technologies available to the farmers are limited, expensive and inadequate, which leads to a lot of vegetable being spoilt and wasted. The inadequacy of appropriate preservation technologies lead to hefty losses during peak harvest periods and serious shortages during off-season period. Technologies like cooling through use of refrigerated stores and containers have been used but are not accessible to most small scale farmers. In addition, electricity supply is not affordable by most farmers, and therefore, electricity operated facilities cannot be used by majority of the farmers in preservation of vegetables. Simple methods like open sun drying have been used by farmers to dry their vegetables for preservation hence prolonging the shelf life by about 3 to 6 months (Chauhan &

Sharma, 1993). However, open sun drying and shade drying expose drying material to weather which can result in spoilage. The material is also subjected to contamination by microorganisms, wind and dust, foreign matter, excreta from animals, and destruction by the animals and human beings. Solar drying technologies can therefore be employed to preserve the high moisture vegetables at relatively low cost.

1.3 Justification

In Kenya, vegetables constitute a significant portion of the horticultural output. In 2003, vegetables constituted about 18% of the 125,000 tonnes of horticultural export volumes (IPAR, 2005). Leafy green vegetables are mainstays in the diets across rural and urban households of Kenya. The consumption of traditional vegetables is increasing significantly amongst the urban population, due to the growing recognition of their high nutritional value. For example, Amaranthus has 13 times more iron and 57 times more Vitamin A than cabbages (IPGRI, 2003). The indigenous leafy vegetables are a very good source of Vitamin A, B complex, C, and E. On average 100g of fresh vegetables, contain levels of calcium, iron, and vitamins that would provide 100% of the recommended daily requirement and 40% for the proteins (Abukutsa-Onyango, 2003). Vegetables are therefore a valuable source of nutrition in rural and urban areas where they contribute substantially to protein, mineral and vitamin intake (Mnzava, 1997). Despite their importance in human life, 30% are spoilt leading not only to food insecurity, but to financial losses for farmers. As such it is crucial that technologies for preserving the leafy vegetables to sustain availability and supply throughout the year are made available and accessible to farmers.

Solar drying is one of the technologies that can be adopted in the preservation of vegetables. Solar drying of vegetables overcomes the drawbacks of traditional open sun drying such as, contamination from dust, insects, birds and animals, lack of control over drying conditions, possibility of chemical, enzymic, and microbial spoilage due to long drying times. Solar drying is advantageous over normal convective dryers like hot air dryer, which requires enormous fuel and energy cost. Solar dried products are of high quality and have better nutrients retention compared to open sun drying. Solar dryers can be made with dark chambers which protect some of the light sensitive nutrients in vegetables from being spoilt by light. Solar drying systems are also easy to use in the rural areas, can be constructed using readily available local material, and are environmentally friendly since they have no emissions to the atmosphere. Solar energy provides simple technologies that can be used to dry the leafy vegetables for preservation. Technologies such as solar cabinet drying, green house tent drying and tunnel drying are some of the systems that can be used. Solar dried vegetables are easy to rehydrate and cook without losing their original appeal. Solar tunnel dryers combined with heat storage system to cater for limited direct solar radiation can be used to dry the high moisture vegetables and hence reduce the wastage and losses experienced by farmers.

1.4 Objectives

1.4.1 General Objective

The general objective of this study is to evaluate thin layer drying characteristics of high moisture content vegetables in a solar tunnel drying system.

1.4.2 Specific Objectives

To modify the existing solar tunnel dryer and evaluate its performance at no load condition.

To evaluate the performance of the solar tunnel dryer in thin layer drying of high moisture content vegetables.

To evaluate thin-layer drying models in characterising drying of high moisture content vegetables in a solar tunnel dryer.

CHAPTER TWO

LITERATURE REVIEW

2.1 Postharvest Food Chains Losses

The problem of postharvest losses is a major obstacle in achieving sustainable food and nutritional security, as these losses reduce farmers' incomes in addition to affecting food supply and availability. Food losses take place at production, postharvest and processing stages in the food supply chain (Parfitt, Barthel & Macnaughton, 2010). Food losses occurring at the end of the food chain at the retail and in final consumption are termed food waste, which relates to retailers and consumers' behaviour. (Parfitt *et al.,* 2010). Food losses or waste constitute mass of food lost or wasted in the part of food chains in which edible products produced for human consumption are disposed without being consumed by human beings. Losses during harvesting are in the form bruises caused by poor harvesting equipment, discarded deformed vegetables, and vegetables not harvested or those discarded because they fail to meet quality standards or are uneconomical to harvest. Some losses occur during handling and storage in the form of vegetables degraded by pests, fungus, and disease. Some losses occur when processing and packaging in the form of spillage, deformation, and use of unsuitable processing methods. For long term storage, food crop must be dried to 12 to 14% of moisture content (wet basis) or lower for most crops, with initial moisture content of 30-80% IDRC (1986). Drying involves the removal of moisture from agricultural produce so as to provide a product that can be safely stored for longer period of time (Scalin, 1997). In addition, drying improves the shelf life and significantly reduces the product volume and weight of the vegetable, while minimizing the packaging, storage, and transportation costs requirements (Chaudhri, Kothari & Panwar, 2009).

2.2 Drying Methods for High Moisture Content Vegetables

2.2.1 Introduction

A number of traditional and advanced techniques are used to accomplish drying. These methods are conventional sun drying, microwave drying, oven drying and solar drying. Sun drying is a conventional heating method where transfer of thermal energy from the product surface towards their centre is slow. The main objective in drying agricultural products is the reduction of the moisture content to a level, which allows safe storage over an extended period. In addition, it brings about substantial reduction in weight and volume, minimizing packaging, storage, and transportation costs (Okos, Narsimhan, Singh & Weitnauer,1992).

2.2.2 Conventional Sun Drying

Open sun drying is a food preservation technique that reduces the moisture content of agricultural products and thereby prevents deterioration during storage (Sacilik, & Elicin, 2006). In open sun drying, the crops are generally spread on the ground, mat, cement floor where they receive short wavelength solar energy during the day and natural air circulation as illustrated in Figure 2.1. A part of the energy is reflected back and the remaining is absorbed by the surface depending upon the colour of the crops. However, there are losses like the long wavelength radiation loss from the surface of crop to ambient air through moist air and convective heat loss due to the blowing wind through moist air over the crop surface.

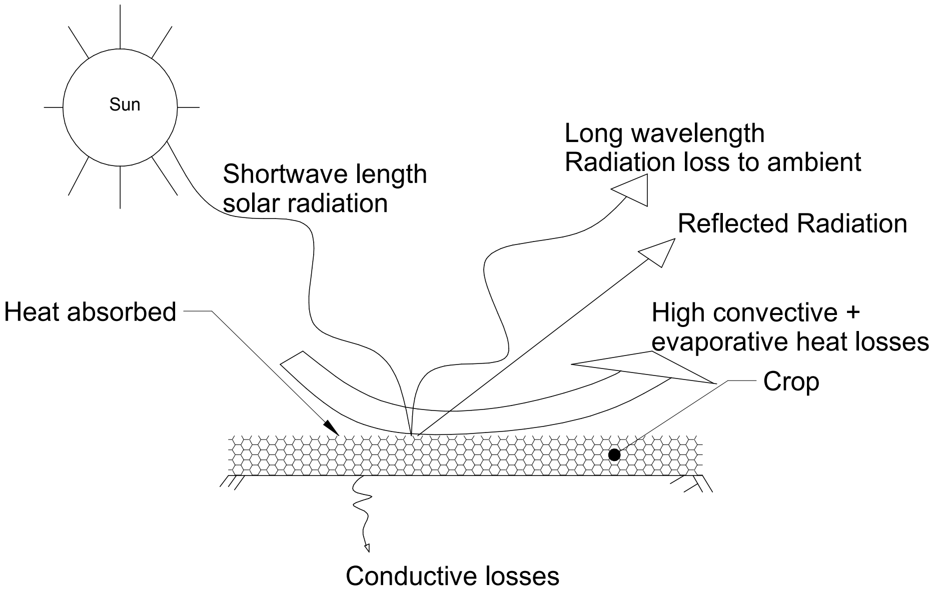

Figure 2.1: Working principles of open sun drying.

(Source: Sharma *et al.,* 2009)

The traditional open sun drying method process is independent of any other source of energy except sunlight and hence the cheapest method. However, the sun's free energy for drying in open-air is counter balanced by a multitude of disadvantages, which reduce not only the quantity but also the quality of the final product (Belessiotis & Delyannis, 2009). Among these limitations are the high crop losses due to inadequate drying which results to fungal attacks, insects, birds and rodents encroachment, unexpected down pour of rain and other weathering effects (Ekechukwu & Norton, 1999). Moreover, since sun drying depends on uncontrolled factors, production of uniform and standard products is not easy to achieve. Due to these inadequacies in open sun drying, solar drying technologies have emerged over time (Sharma, Chen & Lan, 2009). Solar drying provides products with more heat than is available in the open sun condition hence increasing the vapour pressure of the moisture within the crop. Further, relative humidity of the drying air is also significantly lowered thereby increasing the moisture carrying capacity of the drying air and thus ensuring sufficiently low equilibrium moisture content, (Vanderhulst, Lanser, Bergemeyer, Foeth & Albers, 1990).

2.2.3 Solar Drying

Many food industries dealing with commercial products employ state-of-the-art drying equipment such as freeze dryers, spray dryers, drum dryers and steam dryers. The prices of such dryers are significantly high and only commercial companies generating substantial revenues can afford them. In most of the developing countries, commercial dryers are too expensive to consider its purchase. At the village level, probably the most common practice is to spread the harvested product on the ground on a specially prepared area such as on mats, sacks or concrete exposed to the sun. Due to the inherent problems of this open sun drying an alternative that is being encouraged in hot, dry areas of most developing countries is solar drying. In solar drying, solar heat is trapped with a solar collector constructed from a black painted aluminium sheet, (Sharma, Colangelo & Spagna, 1995).The collector is fixed to the drying bin in such a way that an air space exists between it and the bin wall. Energy absorbed by the collector heats the ventilating air by a few degrees as it is forced through the air space.

Various solar energy dryers have been designed around the world. Abdel-Rehim and Fahmy (1998) developed a photovoltaic dryer with dual packed beds for drying medicinal herbs. Their dryer was equipped with electrical heaters powered by a photovoltaic system and variable speed fans to modulate the airflow according to transient changes in solar irradiance and heat output (Wisniewski, 1997). The results indicated that in some specific conditions, e.g. drying of wild grown medicinal plants in remote areas, even application of photovoltaic modules for driving of a fan of a solar dryer is a profitable option and enables easy control of the drying air temperature.

In broad terms, solar drying systems can be classified into two major groups, namely, active solar-energy drying systems most types of which are often termed hybrid solar dryers; and. passive solar-energy drying systems conventionally termed natural-circulation solar drying systems. Each is further classified into three categories namely integral-type solar dryers; distributed-type solar dryers and. mixed-mode solar dryers.

2.2.3.1 ACTIVE SOLAR DRYING SYSTEMS

Active solar drying systems depend only partly on solar-energy, as the source of heat, but employ either solar energy, electrical, fossil-fuel based heating systems or even motorized fans and or pumps for forced convection air circulation. Major applications of active solar dryers are in large-scale commercial drying operations in which air heating solar-energy collectors supplement conventional fossil-fuel fired dehydrators, thus reducing the overall conventional energy consumption, while maintaining control of the drying conditions. However, since electricity, and fossil fuels are either too costly or unavailable at the small-scale farm level, these dryers become undesirable at this farm level.

2.2.3.2 PASSIVE DRYERS

In a passive solar dryer, air is heated and circulated naturally by buoyancy force or because of wind pressure or in combination of both. Normal and reverse absorber cabinet dryer and greenhouse dryer operates in passive mode. Passive solar food dryers use natural means like, radiation and convection, to heat and move the air. These are simple, inexpensive in construction which uses locally available materials occasionally, easy to install and to operate especially at sites not serviced by the national electrical grid. The passive dryers are best suited for drying small batches of fruits and vegetables such as banana, pineapple and vegetables. The passive dryers are of two types namely direct and indirect types. In a direct dryer, food is exposed directly to the sun's rays. This type of dryer typically consists of a drying chamber that is covered by transparent cover made of glass polyvinylchloride sheet.

In the cabinet dryer, of the total solar radiation impinging on the glass cover, a part is reflected back to atmosphere and the remaining is transmitted inside the cabinet, (Figure 2.2). A part of the transmitted radiation is then reflected back from the crop surface and the rest is absorbed by the surface of the crop. This causes its temperature to increase and thereby emit long wavelength radiations, which are not allowed to escape to atmosphere, since the glass cover has very low transmission of radiated long wave from the crop and absorber plate. In order to attain maximum efficiency, reflection and absorption of the glazing material should be as low as possible, whilst transmission shortwave from the atmosphere should be as high as possible (Quaschning, 2005). The overall phenomenon causes the temperature above the crop inside the cabinet to be higher. The glass cover in the cabinet dryer thus serves in reducing direct convective losses to the ambient which plays an important role in raising the temperature of cabinet and product, Sharma *et al.,* (2009).

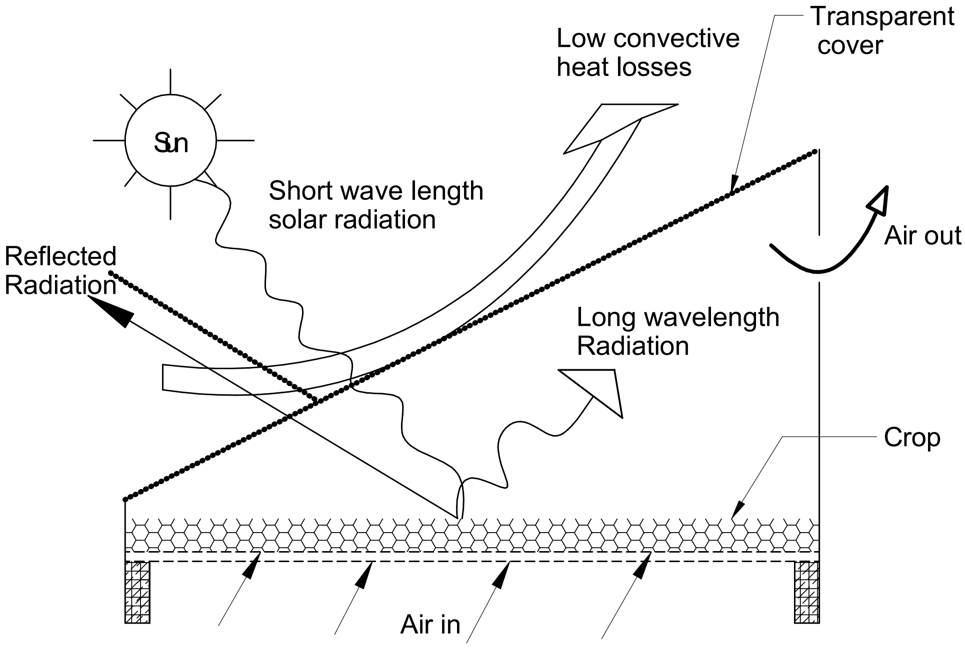

Figure 2.2: Working principles of direct solar drying.

(Sharma *et al.,* 2009)

2.2.4 Heat Storage

A heat sink for storage of heat during the day is included at the base of the heating chamber to reduce intermittent drying due to solar fluctuation. Since, the solar radiation is only available during the day time, it is important to store it during day-time for delivery as needed during the night hours and the periods that clouds cover the sun. The stored energy can be used for continuing the drying process whenever required. Previous studies have shown that heat storage reduces the time it takes to dry a product. Ayensu and Asiedu-Bondzie (1986) constructed a dryer with thermal storage, from locally available materials. The system was capable of transferring 118 W m^{-2} of heat to the drying air. Ayensu, (1997) designed and constructed a solar dryer with a rock storage system. It was found that the rock pile stored enough energy to enhance continuous drying periods of the day with low solar radiation due clouds. The duration of crop drying in the solar dryer was shorter than that in the open air. Aboul-Enein, El-Sebaii, Ramadan and El-Gohary, 2000) developed a solar air heater and tested it with and without thermal storage for drying agricultural products. They found that the drying process would continue at night when a thermal mass was used. El-Sebaii, Aboul-Enein, Ramadan & El-Gohary, 2002) developed a solar dryer with a thermal storage system. The dryer was tested with and without thermal storage and they found that the drying period of seedless grapes was reduced by 12 hours. Mahopac and Ngwalo, (2007) developed an indirect natural convection solar dryer with thermal storage and biomass-back up heater and tested its performance for drying fresh pineapples. They found that the dryer reduced the moisture content of pineapple slices from about 669 to 11% (db.) within 72 hours compared to 120 hours in dryer without het storage and yielded a nutritious dried product. Incorporating sensible and/or latent heat storage media within the solar drying systems therefore accelerates the drying process during night-time and periods of low solar radiation intensity and thus excluding the need for auxiliary heating sources (El-Sebaii, & Shalaby, 2012).

2.3 Perfomance Evaluation of High Moisture Content Vegetable Drying Systems

2.3.1 Introduction

The two methods mainly used for drying perishable foods are air-drying and freeze-drying. Generally, air-drying is favoured due to processing cost and speed (Katsube, Tsurunaga, Sugiyama, Furuno and Yamasaki, 2009). The method can have adverse effects on the taste, colour, and nutritional content of the product, which is very critical to the consumers' perception of the quality of a product. The long drying period and high temperature can also cause a decline in density and water absorbance capacity and a shifting of solutes from the internal part of the drying material to the surface (Tein *et al.,* 1998 and Maskan, 2001). The quality of the final product can therefore be checked through evaluation of several parameters namely β-Carotene, ascorbic acid, and colour.

2.3.2 β-Carotene

Carotenoids are lipid-soluble, yellow, orange, and red pigments produced by plants, algae, and bacteria. In higher plants, carotenoids function in photo protection as light-harvesting antennae pigments and free radical scavengers (Miki, 1991, Taiz and Zeiger, 1998, Tracewell, Vrettos, Bautista, Frank & Brudvig, 2001). Two important dietary carotenoids in human health maintenance are lutein and β-carotene. Increased intake of lutein and β-carotene has been associated with reduced risk of lung cancer and chronic eye diseases such as cataracts and age-related muscular degeneration (Ames, Gold & Willett*.,* 1995; Landrum and Bone, 2001; Marchand, Hankin, Kolonel, Beecher, Wilkens & Zhao, 1993; Semba and Dagnelie, 2003). Increasing the lutein and β-carotene concentrations in vegetable crops through drying techniques would be beneficial to the health status of consumers.

Studies have shown that changes in β-Carotene content of dehydrated savoy beet and amaranth leaves have high content in cabinet dried product than sun dried vegetables. A steady loss in β-Carotene content was observed with increase in storage time and losses were high in ambient than cold stored products. Onayemi and Okeibuno Badifu (1987) reported superiority of cabinet drying over sun drying based on retention of carotenes. Studies on beta-carotene retention in dried vegetables have shown that maximum retention of beta-carotene is obtained by drying vegetables in a the dark chamber of the solar tunnel dryer, compared with open-air sun drying because beta-carotene is very sensitive to direct sunlight (Mulokozi & Svanberg, 2003). Lee, Massey Jr, and Van buren, (1982) reported that carotene appeared to be relatively unaffected by heat processing. Various species of edible leafy vegetables such as spinach, amaranthus, mint, coriander, bengal gram leaves and cauliflower leaves are rich in iron and β-carotene.

2.3.3 Ascorbic Acid

Vitamin C is a highly effective antioxidant and a very small daily intake of this vitamin for an adult is required to avoid deficiency disease scurvy. Even in small amounts it can protect indispensable molecules in the body, such as proteins, lipids (fats), carbohydrates, and nucleic acids (DNA and RNA) from damage by free radicals and reactive oxygen species that can be generated during normal metabolism as well as through exposure to toxins and pollutants (e.g. smoking). High retention of ascorbic acid is an indicator of a good drying system. Ascorbic acid in cabinet dried leaves is higher than in sun-dried leaves, which is attributed to shorter drying time. Maharaj and Sankat (1996) reported higher retention of ascorbic acid in rapidly dried products. Davidek, Velisek & Pokorny, (1990), reported higher losses of ascorbic acid at higher storage temperature. High temperature treatment of leafy vegetables on their carotene contents has varied results on vitamin contents with some depicting increased concentration (Imungi & Potter, 1983).

2.3.4 Chlorophyll

Colour is an important quality attribute in a food to most consumers. It is an index of the inherent good qualities of a food and association of colour with acceptability of food is universal. Among the natural colour compounds, carotenoids and chlorophylls are widely distributed in fruits and vegetables. The preservation of these pigments during dehydration is important to make the fruit and vegetable product attractive and acceptable. Both the pigments are fat-soluble although they are widely distributed in aqueous food systems. Sun drying at ambient temperature results in drastic reduction in chlorophyll content compared to cabinet drying as reported by Negi and Roy (2001). Onayemi and Okeibuno (1987) reported better chlorophyll retention at faster drying conditions. Singh and Tarawali, (1997) studied the effect on compositional quality of commonly consumed green leafy vegetables.

2.3.5 Moisture Content

Moisture content analysis is a critical component of the quality of dried vegetables and is essentially a function of quality control in the drying of vegetables. Moisture content control greatly influences the physical properties and product quality of the dried vegetables and materials at all stages of processing and final product existence (Richardson, 1996). In addition, it influences the physical properties such as weight, density, viscosity, refractive index, electrical conductivity in the drying of vegetables. It therefore indicates the suitability of a dried product to the consumers in terms of storability, nutritional value, agglomeration in the case of powders, microbiological stability, flow properties, viscosity, dry substance content, concentration, or purity, commercial grade of the product, and legal conformity.

The oven drying method is the standard way of determining moisture content of a sample. With this method a vegetable sample is initially weighed and then dried in an oven at 103°C ± 2°C. Drying is continued until the vegetable sample is completely dry (when no further weight loss occurs) and this oven dry weight recorded. The loss in weight during drying indicates how much water was originally present in the vegetable sample and the moisture content can be calculated by Equation (2.1), where Mc_i is the initial moisture content wet basis, M_i is the initial mass of sample at start of drying and M_f the dry weight.

$$Mc_i(\%) = \frac{M_i - M_f}{M_i} * 100 \qquad 2.1$$

2.3.6 Drying Rate

Drying rate is defined by the loss of moisture from the wet solid per each unit of time. It can also be defined more specifically by the differential quotient (dm/dt) when drying air-conditions (viz., temperature, pressure, humidity and velocity) are constant during the drying time (Figure 2.3). The drying rates for drying vegetables can be calculated based on the weight of water removed per unit time per unit weight of dry matter (g $g^{-1}h^{-1}$) (Sankat, Castaigne & Maharaj., 1996; Dandamrongrak, Mason, & Young, 2003; Agarry, Durojaiye, & Afolabi, 2005). The mean drying rate is computed using Equation (2.2). In this Equation (2.2), R_d is the drying rate (g/h), dM is change in mass (g), dt is change in time (h), *t* is the total drying time (h), m_i is the initial mass of vegetable sample (g) and m_f is the final mass of the dried vegetable sample (g).

$$R_d = \left(\frac{dM}{dt}\right) = \frac{m_i - m_f}{t} \tag{2.2}$$

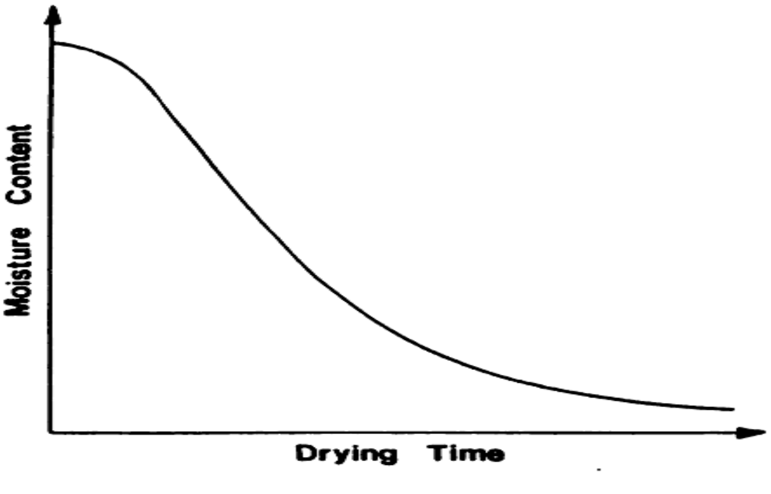

Figure 2.3: Drying rate curve.

2.3.7 Collector Efficiency

The thermal efficiency of a solar collector is the ratio of useful heat gain to the solar radiation incident on the plane of the collector, (Fudholi, Sopian, Ruslan, Othman & Yahya, 2011). It measures how effectively the energy available in the solar radiation is transferred to the flowing air within the system (Tiris, Tiris & Dincer, 1995). Collector efficiency (η_c) (Equation 2.3) is defined as the ratio of useful heat gain (Q_u) over any time period to the incident solar radiation over the same period, with I denoting the solar intensity in W/m^2 and A the collector area in m^2. In Equation (2.3), m is the mass flow rate of air in kg/sec, C_p is the specific heat of air in kJ/kg K, T_o and T_i are the collector outlet and inlet temperature in ^{o}C, respectively.

$$\eta_c = \frac{Q_u}{I * A} = \frac{\overset{*}{m} C_p (T_0 - T_i)}{I * A} \tag{2.3}$$

2.4 Modelling Thin Layer Drying of High Moisture Content Vegetables

2.4.1 Thin Layer Drying

Models are built according to some assumptions; the most common is considering mass transport inside the food as being solely driven by moisture concentration differences, that is a Fickian mechanism. Modelling in a drying process involves vapour/air equilibrium (psychometrics), moisture equilibrium (isotherms), drying kinetics, residence time, and dryer conditions, cost analysis, (Maroulis & Saravacos, 2002). Thin layer drying is based on the assumption that the ratio of air to volume is infinitely large. Considering this assumption, drying rate depends only on the properties of the material to be dried, its size, the drying air temperature, and the moisture content. An empirical Equation predicting the drying time of vegetables is given by Equation (2.4) which is valid for temperatures of below 80°C for solar drying and up to 140°C for convectional and hybrid solar drying (Eissen, 1985). In this Equation, X_t, X_{in}, X_{eq}, and are the moisture content at time *t*, initial and equilibrium, while the parameters *a* and *b* are as shown in below, respectively, while T is the temperature (°C) , (Eissen, 1985).

$$\theta = a.\ln\left[\frac{x_t - x_{eq}}{x_{in} - x_{eq}}\right] + b.\left(\ln\left[\frac{x_t - x_{eq}}{x_{in} - x_{eq}}\right]\right)^2 \qquad (2.4)$$

Where,

$$a = 1.86178 + 0.00488T$$

$$b = 427.2640e^{-0.0301T}$$

2.4.2 Modelling

Simulation models are necessary in the design, construction, and operation of drying systems. Several studies have been done on the mathematical modelling and experimental studies on the TLD processes of various vegetables, fruits and agro based products. This includes studies such as bay leaves (Demir, Gunhan, Yagcioglu, & Degirmencioglu, 2004), laurel leaves (Yagcioglu, Degirmencioglu, & Cagatay, 1999), green pepper, green bean and squash (Yaldiz & Ertekin, 2001), apricot (Togrul & Pehlivan, 2003), eggplant (Ertekin & Yaldiz, 2004), carrot (Doymaz, 2004a) and (Doymaz, 2005).

One of the models that describe thin layer drying characteristics of agricultural products is in the form of the exponential model in shown in Equation 2.5. The model assumes negligible resistance to moisture movement to the surface of the material and that the resistance to moisture movement is concentrated on the surface of the material. (Temple & Boxtel, 1999)

$$M.R = \frac{M - M_e}{Mo - M_e} = \exp\,(kt) \qquad (2.5)$$

Where,

MR is the moisture ratio, M the moisture content at any time t (% wb), M_e the equilibrium moisture content (emc) at the conditions of the drying air (% wb), M_o the initial moisture content of sample (% wb), t the drying time (min), and k is the drying constant (min^{-1}).

However, information about the drying kinetics of high moisture content vegetables in solar tunnel dryer is not available in the literature hence the need for this research. The most widely investigated theoretical model in the drying of different foods is given by the solution of Fick's second law (Doymaz and Pala, 2002; Sacilik, Keskin, & Elicin, 2005; Diamante & Munro, 1993; Liu & Bakker-Arkema, 1997). The uni-dimensional Fick's law is often used to describe a moisture diffusion process, as shown in Equation (2.6). In the Equation, M is the local moisture content (db), t is time (s), L is the half thickness of vegetable (m), and D_{eff} is the effective diffusivity (m^2/s).

$$\frac{\partial M}{\partial t} = D_{eff} \frac{\partial^2 M}{\partial L^2} \tag{2.6}$$

To apply Fick's law, the food product is assumed to be uni-dimensional, have uniform initial moisture content, and have internal moisture movement as its main resistance to moisture transfer. In Equation (2.7), (Okos et al., 1992) gives the solution of Fick's law for a sample slice piece. In this Equation, L is the half-thickness of the vegetable sample.

$$\frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-(2n+1)^2 \pi^2 \frac{D_{eff} t}{4L^2} \right) \tag{2.7}$$

For long drying times, *n* becomes 1.The effective moisture diffusivity (D_{eff}) is determined by applying logarithms to Equation (2.7) to obtain a linear relation of the form shown in Equation (2.8).

$$\ln MR = \ln\left(\frac{M - M_e}{M_0 - M_e} \right) = \ln\left(\frac{8}{\pi^2} \right) - \left(\frac{\pi^2 D_{eff} t}{4L^2} \right) \tag{2.8}$$

2.4.3 Effective Diffusivity

The effective diffusion coefficients (D_{eff}) are typically determined by plotting experimental drying data in terms of ln (MR) versus time (Ozdemir & Devres, 1999; Ayensu, 1997; Doymaz, 2009; Karathanos & Belessiotis, 1999) which gives a straight line with a slope S given by Equation (2.9).

$$S = \frac{\pi^2 D_{eff}}{4L^2} \tag{2.9}$$

The collected moisture data was used to calculate the moisture ratio using Equation (2.5) and plot graphs of moisture content against drying time, and to evaluate different models in Table 2.1, which are based on the theory of thin layer drying.

Table 2.1: Thin layer drying models for agricultural products

Model No.	Model Equation*	Model name
1	$MR = \exp(-kt)$	Newton
2	$MR = \exp(-kt^n)$	Page
3	$MR = a \exp(-kt)$	Henderson and Pabis
4	$MR = a \exp(-kt) + c$	Logarithmic
5	$MR = a \exp(-k_1 t) + b \exp(-k_2 t)$	Two-Term
6	$MR = a \exp(-kt) + (1-a) \exp(-kat)$	Two-Term Exponential
7	$MR = \exp(-kt)^n$	Modified Page
8	$MR = a \exp(-kt) + (1-a) \exp(-gt)$	Verma et al..
9	$MR = a \exp(-kt) + (1-a) \exp(-kbt)$	Diffusion approximation

* *a, b, c*, *g* and *n* are drying coefficients, *t* is drying time (hours) and *k* is drying constant (h^{-1}) (Doymaz and Pala, 2002; Sacilik et al., 2005; Diamante and Munro, 1993; Liu and Bakker-Arkema, 1997).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Description of Experimental Site

The study was conducted at the Agricultural and Biosystems Engineering Department of Jomo Kenyatta University of Agriculture and Technology (JKUAT), Kenya. 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, F.N., Wamicha, W. N., & Njoroge, C.R., (1978). The region experiences bimodal rainfall pattern with cold, rainy seasons between April and August, and October and December each year, the rest of the period being dry hot seasons (Watako, Ndung'u, Ngamau, & Suguira, 2001). The ten year mean clearness index for Juja in the cold rainy season is 0.47, while during the dry hot seasons its 0.66 (NASA).

3.2 Modifying the Existing Solar Tunnel Dryer and Evaluating its Perfomance at No Load Condition

3.2.1 Description of the Existing Solar Tunnel Dryer

An existing dryer (Figure 3.1 and Plate 3.1) at JKUAT University, previously studied by Kituu, Shitanda, Kanali, Mailutha, Njoroge, Wainaina, and Silayo, (2010) in thin drying of tilapia fish was used for this study. The dryer comprises of the various sections namely the solar collector surface, heating chamber and the drying chamber.

The cover of the collector plate was made of glass, and prevents dust and rain from coming in contact with the collector plate, and prevent heat loss. The collector plate, 19mm thick, and rectangular was fitted on top of the heating chamber. The plate was made of galvanized iron (GI) and painted black for enhanced absorption and emission of solar energy, and has a flat glass cover-plate (Kituu *et al.,* 2010). On the other hand, the heating chamber measured 2.44m long, 1.22m wide, and 0.54m high. The bottom plate of the tunnel section was made of GI sheet coated with aluminium paint, to reflect energy incident on the surface. The rear side wall of the chamber was made of aluminum coated GI sheet while the front wall has two sets of overlapping doors through which thermocouples from various data logger channels were inserted inside the dryer. Further, the inner walls of the doors were made of aluminium coated GI sheets, whereas the bottom and the side walls of the sheets were insulated with soft-board which was sandwiched between the inner and outer GI sheets to minimise energy losses (Kituu *et al.,* 2010). The drying chamber had two sections (i.e., rectangular and tapered sections). The rectangular section measured 1.22m long, 0.9m wide, and 0.7m high while the tapered section measured 1.22m by 0.7m at the bottom, and 0.2m by 0.2m at the narrow end. The chamber was made of GI sheets, with aluminum in the inner walls while the outer walls were painted black. An exhaust chimney was fitted at the top of the drying chamber and was lined with acrylic glass to trap solar energy for heating the exhaust air to enhance natural air convection (Kituu *et al.,*2010).

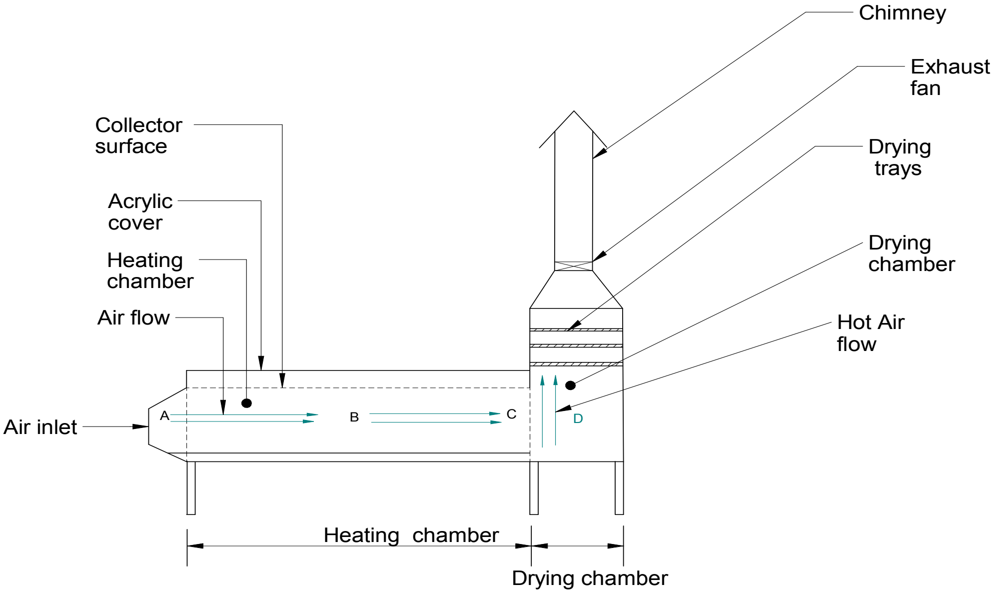

Figure 3.1: Schematic diagram of unmodified solar tunnel dryer.

Plate 3.1: Unmodified solar tunnel dryer.

3.2.2 Evaluating the Performance of the Existing Solar Tunnel Dryer

The performance of existing solar tunnel dryer was evaluated by conducting test runs at no load for three days, where no load in this case means that no drying was taking place. Temperature and relative humidity of ambient air and air flowing through the system was recorded at points A, B and C (Figure 3.1) using digital data loggers (HOBO U30 Onset, MA, USA) (Plate 3.2). Solar radiation was recorded using a solar radiation sensor (Silicon Pyranometer smart sensor, model S-LIB-M003) which was mounted on the HOBO weather station logger. The data was later uploaded in the computer for analysis. The data obtained in Section 3.2.2a was analysed to show the variation of, solar radiation, temperature and relative humidity in the ambience and in the solar tunnel dryer at no load over the test period. Anova test was conducted to establish existence of significant difference between the ambient and solar tunnel parameters. The data was also presented in graphical form using Ms Excel^{TM}.

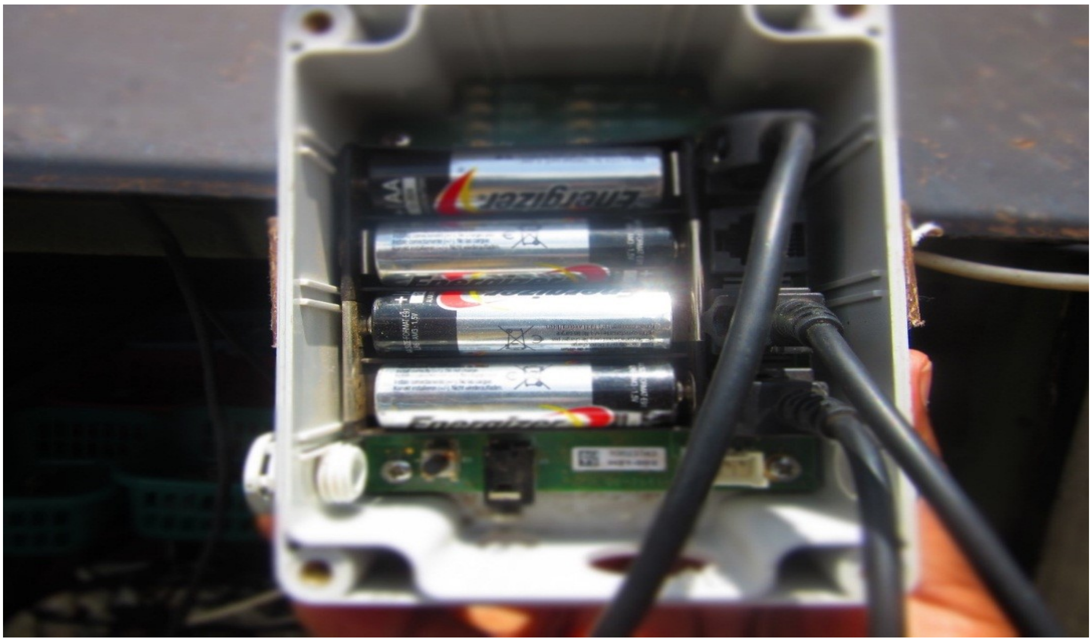

Plate 3.2: Data logger set.

3.2.3 Modifying the Existing Solar Tunnel Dryer

Modifications was done on the existing solar tunnel dryer which focuses on the cover plate, the heating chamber and air flow through the system. The flat cover plate was replaced with a parabolic cover plate to enhance drainage of water and dust from the surface (Figure 3.2 and Plate 3.3). The parabolic section had a radius of 0.75m and a tangent angle of 45^o for easy drainage. A 100W solar panel was fitted to run a 12V, 0.16A, 1.92W d.c. suction fan at the base of the chimney, with output of $1.2m^3/s$ of air for enhancement of air flow through the dryer, (Kituu *et al.,* 2010). A heat sink in form of riverbed stones was added at the base of the heating chamber to store heat and release during low solar incident periods. The stored energy was used for continuing the drying process whenever required. The heat storage unit was packed riverbed stones (1.9-2.54cm in diameter) occupying a volume of 2.44 x 1.2 x 0.09m or $0.26\ m^3$, which was the average of the limit volume of 0.15 to 0.35 m^3 recommended by Goswani, (1986). Riverbed stones are locally available, clean and have a higher thermal conductivity (0.7 W/ (m.K) compared to sand (0.15 - 0.25W/ (m.K).

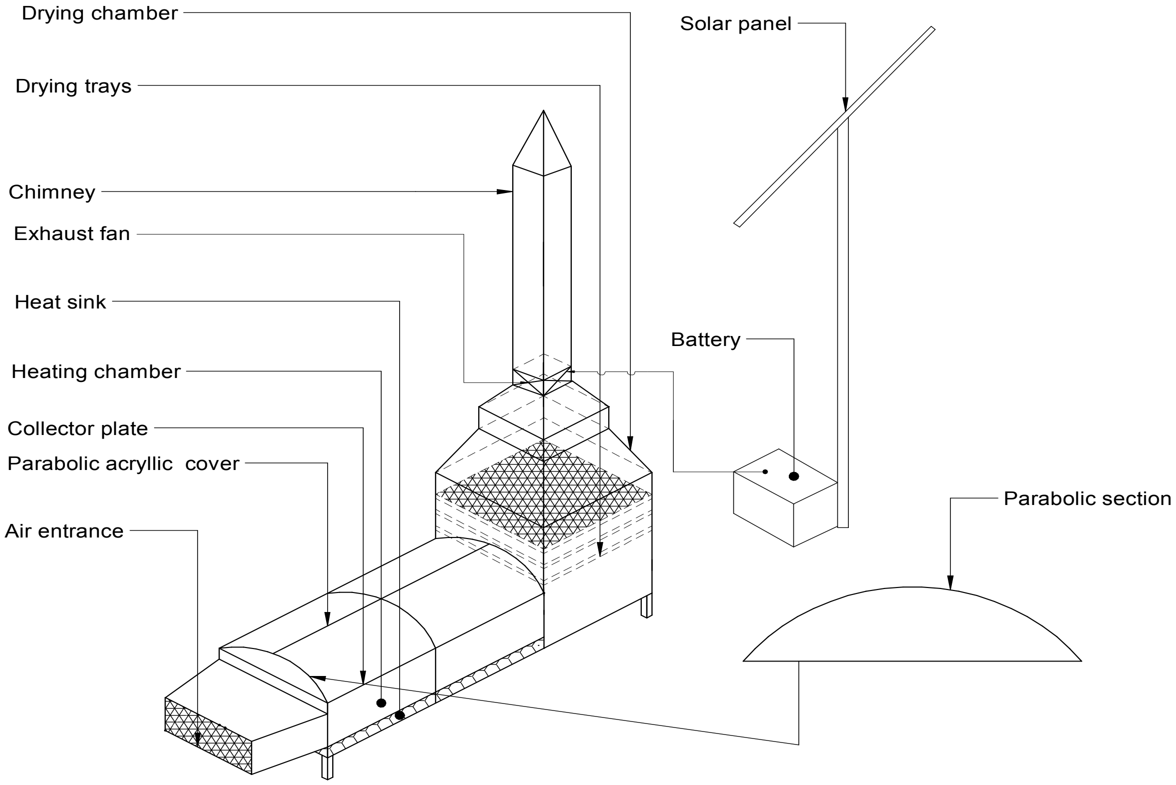

Figure 3.2: Isometric view of modified solar tunnel dryer.

Plate 3.3: Modified solar tunnel dryer.

3.2.4 Evaluating the Performance of the Modified Solar Tunnel Dryer

The performance of modified solar tunnel dryer was evaluated by conducting test runs at no load for three days on 24th to 26th February 2015. Temperature and relative humidity of ambient air and air flowing through the system was recorded at points A, B and C (Figure 3.3) using digital data loggers in Section 3.1.2. Solar radiation values were recorded simultaneously together with the other parameters at 15minute intervals. The data recorded was statistically evaluated for any significant difference between the two systems. The collector efficiencies was analysed using Equation (2.3) as defined earlier in Section 2.3.7

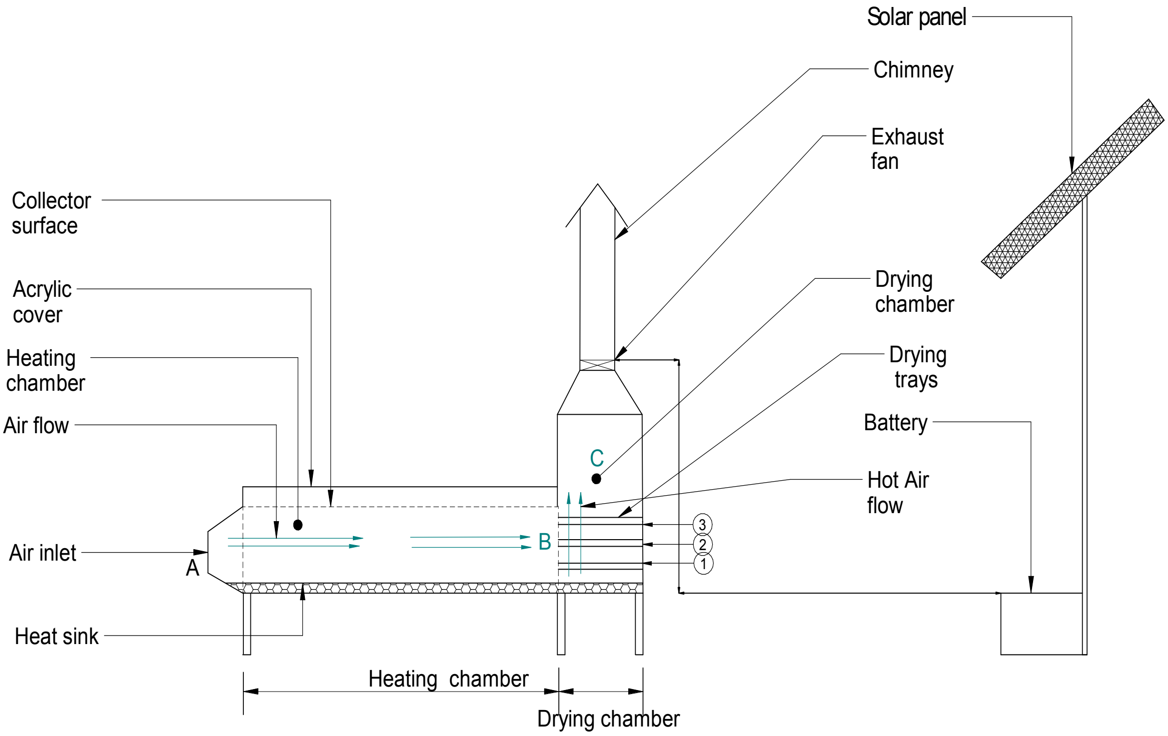

Figure 3.3: Schematic diagram of the modified solar tunnel dryer.

3.3 Evaluating the Performance of the Modified Solar Tunnel Dryer in Drying of High Moisture Content Vegetables

3.3.1 Data Acquisition

In order to evaluate the performance of the modified dryer and evaluate thin layer models in drying of high moisture content vegetables, five different types of vegetables (viz., cabbage, kale, cowpeas, stinging nettle, and amaranth) were assessed. Four of the vegetables (viz., cabbage, kales, amaranth and cowpeas) were obtained from JKUAT farm while stinging nettle was sourced from local vegetable markets in Githurai in Kiambu County. To minimise moisture loss during transportation, the vegetables were wrapped in polybags and placed inside sealed plastic buckets and taken to the food processing lab for preparation. The vegetables were sorted to remove dust and any foreign materials and to cool them down to room temperature. Cabbages and kales leaves were sliced to uniform shreds of 2cm. The sizes of the other three vegetables (i.e., amaranth, stinging nettle and cowpeas) were not sliced since they were relatively small in size. The vegetables were dried each type at a time. For each vegetable type, twelve (12) samples weighing 100g each were used in the study. A digital scale (Model PB3002, Mittler Toledo, Switzerland) with sensitivity of 0.1gm was used in the study. The samples were placed on plastic trays (44cm long by 32cm wide by 5cm deep) and then randomly divided into two (2) sets, experimental and control. The experimental set was placed in the drying chamber at level 1, 2, and 3 while the control set was placed in the open sun. The samples were continuously weighed at 30min interval as drying progressed.

During drying, the temperature and relative humidity, outside and inside the drying chamber and the solar radiation flux incident on the cover plate was recorded at points A, B and C (Figure 3.5), using HOBO mini weather station logger at 15 minutes interval between 9.00am and 6.00pm. The quality of the dried vegetables was analysed based on colour, ascorbic acid and carotene levels. The colour of the samples was measured at the start of drying and at the end of the drying period. Colour was captured using Minolta colour difference meter (Model CR-200, Osaka, Japan). The colour parameters that were measured were lightness ($L*$), redness ($a*$), yellowness ($b*$). Ascorbic acid level was determined by proximate composition analysis methods described by the Association of Official Analytical Chemists (AOAC, 1990). Similarly, β-carotene levels was determined using AOAC (1990) spectrophotometric method involving extraction of pigment with 1:1 v/v acetone-n hexane solution, saponification, and isolation of unsaponified extract using methanolic potassium hydroxide. Both ascorbic acid and beta carotene were analysed at the end of the drying process in the food science laboratory in JKUAT.

3.3.2 Data Analysis

The data for moisture content of the vegetables, temperature and relative humidity were used to establish relationships between moisture content, moisture ratio, dying rate, relative humidity and temperature with drying time. The dry basis moisture content, Mdb, at drying time *t* (hrs) was determined using Equation (3.1), where m*i* is the initial weight of sample before drying and m_t is the weight of sample at time (*t*).

The relation between moisture content and drying time was based on the Newton model of thin layer drying, and observations by (Kingsly, Goyal, Manikantau, and Ilyas, 2007) and (Uluko, Kanali, Mailutha, & Shitanda, 2006) for material drying under varying relative humidity as in solar drying.

$$MC_{db} = \frac{m_i - m_t}{m_t} \times 100 \tag{3.1}$$

The drying rates of the vegetables was calculated based on the weight of water removed per unit time per unit weight of dry matter, expressed in units of g $g^{-1}h^{-1}$ (Sankat *et al.,* (1996), Dandamrongrak *et al.,* (2003), Agarry *et al.*, (2005). The overall drying rate was computed using Equation (3.2), where, R_d is the drying rate (g $g^{-1}h^{-1}$), dM is change in mass (g), dt is change in time (h), t is the total drying time (h),and m_i is the initial sample mass (g),m_f is the final dried sample mass(g).

$$R_d = \left(\frac{dM}{dt}\right) = \frac{m_i - m_f}{t} \tag{3.2}$$

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). To apply Fick's Law, the food product is usually assumed to be uni-dimensional, have uniform initial moisture content, and have internal moisture movement as its main resistance to moisture transfer. Diffusivity, which indicates the flow of moisture out of the material being dried, was calculate using Equation (3.3) where, m is the local moisture content (%db), D_{eff} is the effective moisture diffusivity (m^2s^{-1}) and L is the half thickness of vegetable (m), (Saravacos *et al.*, 2002).

$$\frac{\partial m}{\partial t} = D_{eff} \frac{\partial^2 m}{\partial L^2} \tag{3.3}$$

The solution of Fick's law for a sample slice piece is given by Equation (3.4) (Okos *et al.,* 1992). In this Equation, M_e is the equilibrium moisture content and L is the half-thickness of the vegetable sample.

$$\frac{M_t - M_e}{M_0 - M_e} = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-(2n+1)^2 \pi^2 \frac{D_{eff}t}{4L^2}\right) \tag{3.4}$$

For long drying times, which are typical in the drying of vegetables, *n* in Equation. (3.4) becomes 1. The effective moisture diffusivity (D_{eff}) was determined by applying logarithms to Equation (3.4) to obtain a linear relation of the form shown in Equation (3.5).

$$\ln MR = \ln\left(\frac{M_t - M_e}{M_0 - M_e}\right) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}t}{4L^2}\right) \tag{3.5}$$

The coefficients (D_{eff}) was determined by plotting experimental drying data in terms of ln(MR) versus time (*t*) (Ozdemir and Devres, 1999; Ayensu, 1997; Doymaz, 2004; Karathanos and Belessiotis, 1999) which gave a straight line with a slope S given by Equation (3.6).

$$S = \frac{\pi^2 D_{eff}}{4L^2} \tag{3.6}$$

The colour ($L^*a^*b^*$) of the vegetables was measured at the start and end of the drying period using Minolta colour difference meter (Model CR-200, Osaka, Japan). The colorimeter was calibrated before taking measurements of each sample on a standard white plate (Minolta Calibration plate no. 15033256). The parameters of colour lightness (L^*), redness (a^*), yellowness (b^*), were measured and Hue angle, H^*, which measures the colour the eye is able to perceive was given by Equation (3.7) (Mohammadi, Rafiee, Emam-Djomeh & Keyhani. 2008). In the Equation, H^* is the attribute of colour that is related to the perceived colours: red, yellow, green and blue or a combination of two of them. Finally, L_o^* is initial value of L^*, a_o^* is initial value of a^* and b_o^* initial value of b^*.

$$
\begin{aligned}
H^{*} &= \tan^{-1}\left\{\frac{b^{*}}{a*}\right\} \; for\, a^{*} > 0,\; b^{*} > 0 \\
&= \left(180 + \tan^{-1}\left\{\frac{b^{*}}{a^{*}}\right\}\right), \;\; for\, a^{*} < 0,\; b^{*} > 0; \\
&\qquad\qquad\qquad and\ for\ \ a^{*} < 0,\; b^{*} < 0, \\
&= \left(360 + \tan^{-1}\left\{\frac{b^{*}}{a^{*}}\right\}\right), \;\; for\, a^{*} > 0,\; b^{*} < 0
\end{aligned}
\qquad (3.7)
$$

From the computed values for hue angle, the colour of the vegetables was evaluated using a CIE-L.a.b colour chart plot (Figure 3.4).

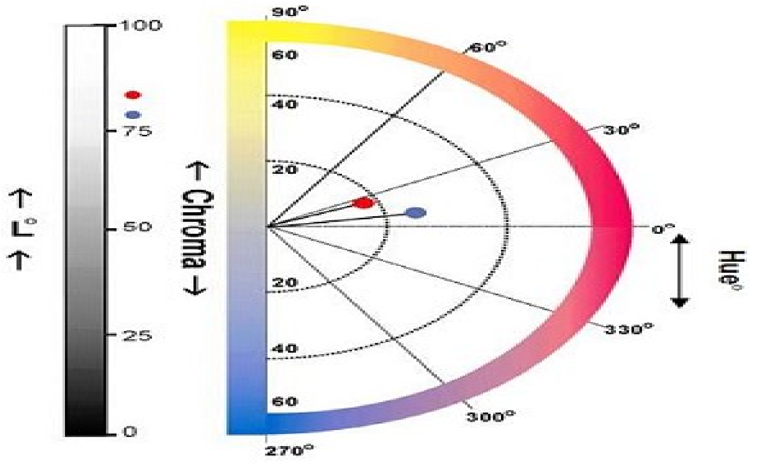

Figure 3.4: A CIE-L.a.b colour chart plot.

(Source: Mohammadi, 2008).

Ascorbic acid content was determined by titration based on the standard AOAC (1980) method. It was then calculated using Equation (3.8), where, Vit.C is Vitamin C content (mg/100gDM), VE the vitamin C equivalent of 1 ml of 2,6-Dichlorophenolindophenol

(DCPIP) (mg/ml), V_1 the total extract volume (ml),V_2 the titrated extract volume (ml), S the sample weight (g), and Y the sample dry matter (%).

$$Vit\,C = \frac{Titre \times VE \times V_1 \times 100 \times 100}{V_2 \times S \times 1000 \times Y} \tag{3.8}$$

Further, in order to establish quality of the dried product the β-Carotene levels were analysed and the results used to compare with other products dried in different methods. The β-carotene levels of the dried vegetables was analysed using AOAC (1980) spectrophotometric method involving extraction of pigment, from which the β-carotene (mg/100g) level was calculated using Equation (3.9). In the Equation, T is absorbance, V is volume of eluate (ml), L is depth of cuvette (cm), W is original weight of sample (mg), $E^{\%}_{1cm}$ (=43,336 nm).

$$\beta - carotene = \left(-\log T * V * 100\right) / \left(E^{\%}_{1cm} * W\right) \tag{3.9}$$

3.4 Evaluating the Drying Characteristics of High Moisture Content Vegetables Using Thin Layer Solar Drying Models

The data obtained in Section 3.2.1 was used to establish the most suitable models from Table 2.1 which would best describe the drying of each of the vegetables in the solar tunnel dryer. The experimental data was fitted in these models in the form of changes in moisture ratio versus drying time, which was calculated using Ms Excel software. The moisture ratio values in the Equations was simplified to M/M_o instead of the $(M-Me)/(M_o-Me)$ due to continuous fluctuation of relative humidity of drying air during solar drying (Midilli & Kucuk, 2003).

The suitability of the models in prediction of the drying of the vegetables in the solar tunnel dryer was evaluated using the coefficient of determination (R^2), root mean square error (RMSE) and reduced chi-square (χ^2) as presented in Equations (3.10-3.12), where $MR_{act,i}$ and $MR_{pre,i}$ are the actual and predicted moisture ratios, respectively, N and nc are the number of observations and constants found in the respective model, respectively (Doymaz *et al.*, 2004; Sarsavadia, Sawhney, Pangavhane & Singh, 1999). The acceptability of the best model was based on how close to one (1) the value for the R^2 was, and how low the values for the reduced chi-square (χ^2) and root mean square error (RMSE) were (Doymaz *et al.,* 2004). The absolute residual error (ε), as defined by Equation (3.13), was further used to confirm the suitability of the models (Kanali, 1997). The prediction performance (η_p) of the models were based on residual error intervals of 10% using Equation 3.14, where Nc and Nt represents the number of correctly predicted and trial data, respectively (Uluko *et al.*, 2006)

$$R^2 = 1 - \left(\frac{\sum_{i=1}^{N} \left(MR_{pred,i} - MR_{\exp,i} \right)^2}{\sum_{i=1}^{N} \left(\overline{MR_{pred}} - MR_{pred,i} \right)^2} \right) \tag{3.10}$$

$$RMSE = \left(\frac{1}{N} * \sum_{i=1}^{N} \left(MR_{pred,i} - MR_{act,i} \right)^2 \right)^{1/2} \tag{3.11}$$

$$\chi^2 = \left(\frac{\sum_{i=1}^{N} \left(MR_{pred,i} - MR_{act,i} \right)^2}{N - n} \right)^{1/2} \tag{3.12}$$

$$\varepsilon(\%) = \left| \frac{MR_{pred,i} - MR_{act,i}}{MR_{act,i}} \text{ x } 100 \right| \tag{3.13}$$

$$\eta_p(\%) = \frac{N_c}{N_t} * 100 \tag{3.14}$$

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Modified Solar Tunnel Dryer

The solar tunnel dryer was modified as shown in Figure 3.3. In the figure the cover of the collector plate was modified from flat to a curved one in order to improve self-drainage and reduce dust and other foreign objects settling on the surface. Black riverbed stones were also added in the heating chamber in order to improve heat storage and regulate temperature fluctuation of the drying air during off-sunshine hours such as cloudy periods of the day (Plate 4.1).

Plate 4.1: River bed stones.

4.2 Performance of Modified Dryer at No Load

The mean drying chamber and ambient temperatures at different times of the day are presented in Figure 4.1, as recorded on 24th to 26th February 2015. In the figure, T_a, T_i, and T_o are the ambient, inlet and outlet temperatures, respectively, in °C, while S.R is the solar radiation in W/m^2. The results show that the temperatures increased as the day progressed with highest values of 54.4 and 33.6°C being recorded at the inlet to the drying chamber and ambient, respectively, at. 3.00pm. Comparison of the solar tunnel dryer and open sun indicates that temperatures were significantly higher (p-value=1.17×10^{-06}, $F_{crit,5\%}$=4.196, $F_{computed}$=38.039) for the former than the later at 5% significant level (Table 4.1). This shows that the solar tunnel dryer harnesses more energy than the open sun as previously observed by Navale, Harpale, and Mohite, (2015) in the comparison of open sun and cabinet solar drying for fenugreek leaves. The study showed drying time shortened from seven to four hours when drying fenugreek leaves in a cabinet solar than in the open sun at 87% (w.b) moisture content.

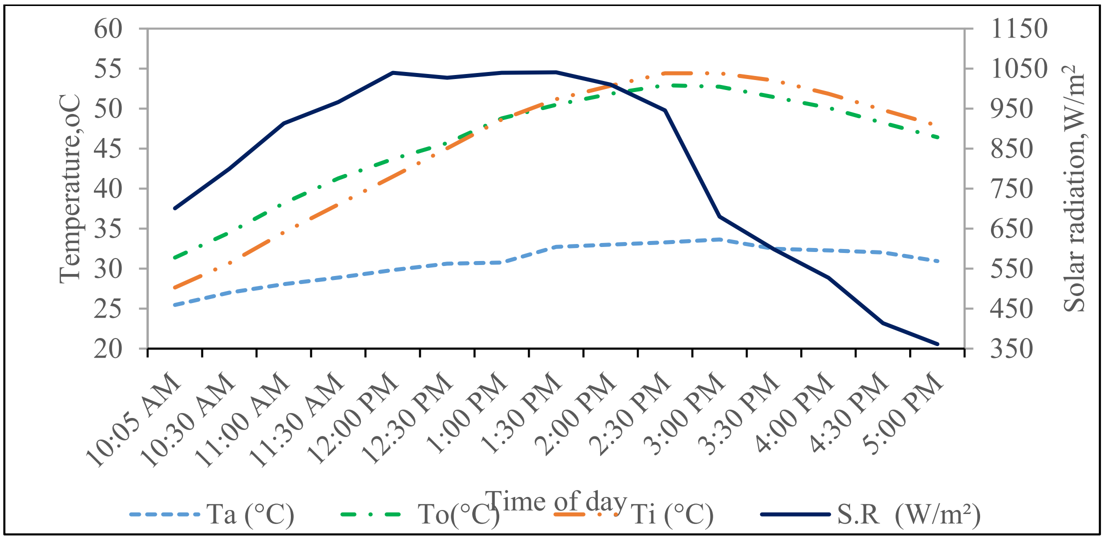

Figure 4.1: Temperature at dryer inlet, outlet and open sun.

Table 4.1: Temperature ANOVA results for air in solar tunnel dryer and open sun

Source of Variation	SS	df	MS	F	P-value	F crit
Drying condition	1628.362	1	1628.362	38.03867	$1.17\text{x}10^{-6}$	4.195972
Residual	1198.626	28	42.80808			
Total	2826.989	29				

In the table: SS= sum of squares, df= degrees of freedom, MS= mean sum of squares, F_{crit}= F-statistic, F= $F_{computed}$

An analysis of variance for temperature at the inlet and outlet of the dryer and open sun yielded the results shown in Tables 4.2. The results (p-value=3.67×10^{-16}, $F_{crit,5\%}$=3.080, $F_{computed}$=50.289) show that there was significant difference in the collector, dryer and open sun temperatures. However, there was no significant difference (p-value=0.294288, $F_{crit,5\%}$=3.974, $F_{computed}$=1.116) between the inlet and outlet temperatures of the dryer chamber (Table 4.3).

Table 4.2: Temperature ANOVA results for air at inlet and outlet of drying chamber and open sun

Source of Variation	SS	df	MS	F	P-value	F crit
Drying condition	3997.624	2	1998.812	50.28892	$3.67\text{x}10^{-16}$	3.080387
Residual	4292.63	108	39.74658			
Total	8290.255	110				

Table 4.3: Temperature ANOVA results for air at inlet and outlet of drying chamber

Source of Variation	SS	df	MS	F	P-value	F crit
Drying condition	77.86656	1	77.86656	1.116116	0.294288	3.973897
Residual	5023.126	72	69.76564			
Total	5100.992	73				

The lowest and highest values of relative humidity in the collector chamber were 9.0% at 3.00pm and 42.8% at 10.00 am, respectively, against 24.4 and 46.5% for the open sun, respectively (Figure 4.2). In Figure 4.2, RH_i, RH_o, and RH_a are dryer inlet, outlet and ambient relative humidity, respectively. The relative humidity values for the air in the solar dryer were consistently lower than for ambient air meaning that the dryer was more suitable for drying than the convectional open sun commonly practiced by farmers. The observed average minimum and maximum solar radiation during the test days were 361.4W/m^2 at 5.00pm and 1040.6W/m^2 at 1.30pm, respectively, while the average solar radiation for the test period was 804.2±240.6W/m^2. Similarly, the results (p-value=$4.42\text{x}10^{-5}$, $F_{crit,5\%}$=3.080, $F_{computed}$ =11.017) show that there was significant difference in the relative humidity at inlet and outlet of the drying chamber, and open sun (Table 4.4). This indicates that the dryer attains lower relative humidity than the surrounding, which is good for drying. The results agreed with earlier studies that observed that relative humidity decreases with increase in temperature (Basunia and Abe, 2001).

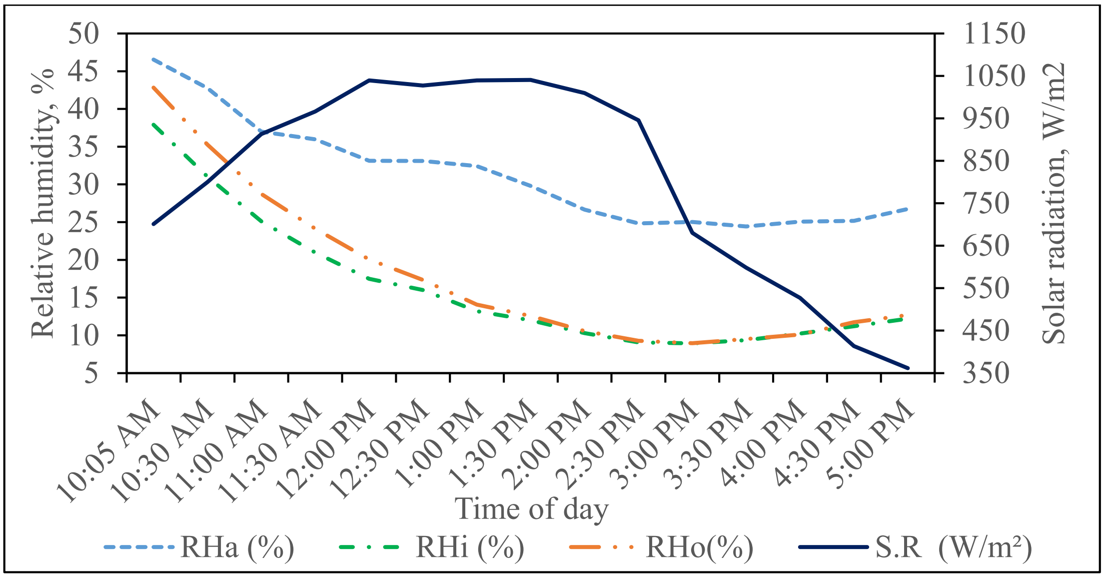

Figure 4.2: Solar radiation and relative humidity at dryer inlet and outlet and in the open sun.

Table 4.4: Relative humidity ANOVA results for air at inlet and outlet of drying chamber and open sun

Source of Variation	SS	df	MS	F	P-value	F_{crit}
Drying condition	4272.309	2	2136.154	11.01718	4.42×10^{-5}	3.080387
Residual	20940.44	108	193.893			
Total	25212.75	110				

The dryer efficiency before and after modification were 41.8 and 51.3%, respectively, based on Equation (2.3). In the Equation, A_c=2.98m^2, $\dot{m} = 0.083$ kg/s, I=916.5 W/m^2, ρ=1.21kg/m^3, C_p=1.005 kJ/kg K. It was observed that the efficiency of the dryer improved by 9.5% after modification.

4.3 Perfomance of the Modified Dryer in Drying High Moisture Content Vegetables

4.3.1 Performance Based on Temperature Before and After Modification at No Load

An analysis of variance for collector temperatures before and after dryer modification yielded the results shown in Table 4.5. The results show that there was no significant difference (p-value=0.955, $F_{crit,5\%}$=4.225, $F_{computed}$=0.003) in the collector temperatures before and after dryer modification although the average temperatures were slightly higher for the modified dryer (45.5±8.9) than the unmodified one (45.1±9.1°C). Similarly, the results show that there was no significant difference (p-value=0.779, $F_{crit,5\%}$=4.225, $F_{computed}$=0.080) in the relative humidity in the dryer before and after modification at no load (Table 4.6).

Table 4.5: Collector temperatures ANOVA results before and after modification at no load

Source of Variation	SS	df	MS	F	P-value	F crit
Drying condition	0.272057	1	0.272057	0.003224	0.955157	4.225201
Residual	2194.252	26	84.39431			
Total	2194.524	27				

Table 4.6: Collector relative humidity ANOVA results before and after modification at no load

Source of Variation	SS	df	MS	F	P-value	F crit
Drying condition	4.284057	1	4.284057	0.080342	0.779079	4.225201
Residual	1386.392	26	53.32277			
Total	1390.676	27				

4.3.2 Performance Based on Drying Characteristics of the Vegetables

4.3.2.1 Moisture Content

The vegetables dried from an initial moisture content of 1288.9, 669.2, 474.7, 566.7, and 566.7% to final moisture content of 7.57, 10.41,5.05,7.29 and 3.55 (dry basis) for cabbages, kales, stinging nettle, amaranth and cowpeas, respectively, using the modified dryer. The drying curves for the vegetables (viz., cabbage, kales, amaranth, cowpeas and stinging nettle) dried using the solar tunnel dryer and under the open sun are presented in Figures 4.3-4.7. The results show that all the vegetables had fast rates of moisture loss within the first four (4) hours before slowing down thereafter. This behaviour is consistent with drying of most biological material and confirms to similar observations by Abalone, Cassinera, Gastón, & Lara, (2006) and Basunia and Abe (2001), hence, thin layer drying models shown in Table 2.1 can be applied to predict the drying behaviour of these vegetables. The longer drying time for cabbages in both methods was associated to its higher moisture content (1288.9%) compared to the other four vegetables. It was also observed that open sun dried vegetables stabilised at higher final moisture content compared to the solar tunnel dried ones.

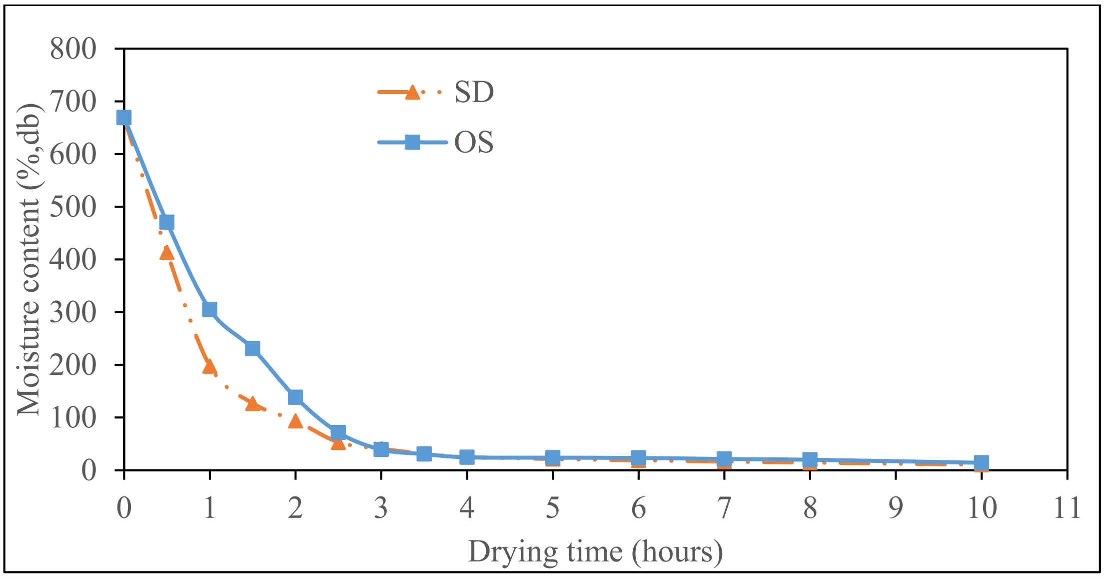

Figure 4.3: Overall drying curves of kales in the solar tunnel dryer and open sun.

(SD=solar dryer; OS=open sun)

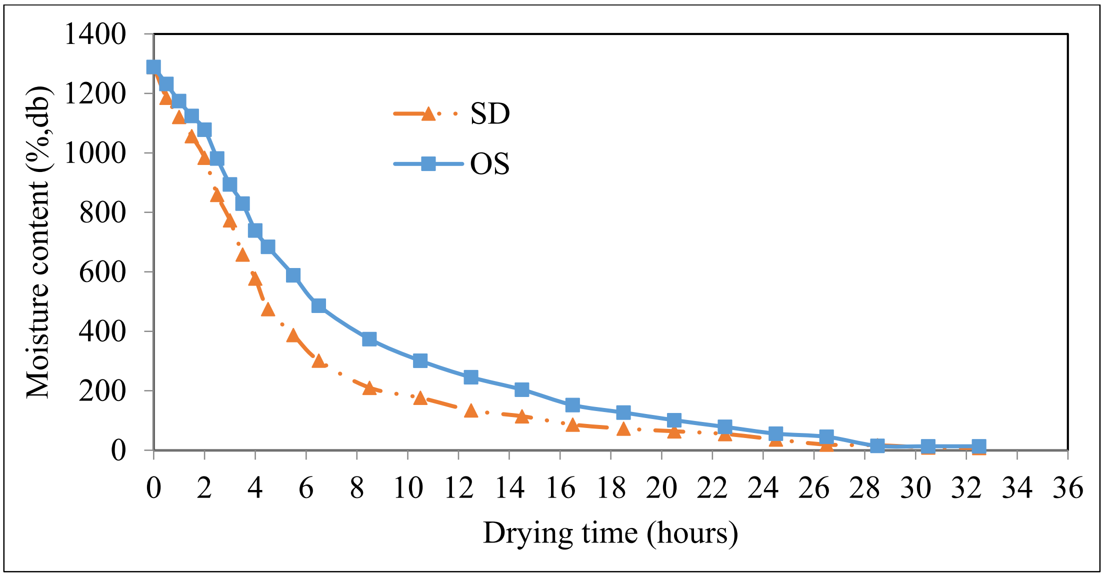

Figure 4.4: Drying curves of cabbage in the solar tunnel dryer and open sun.

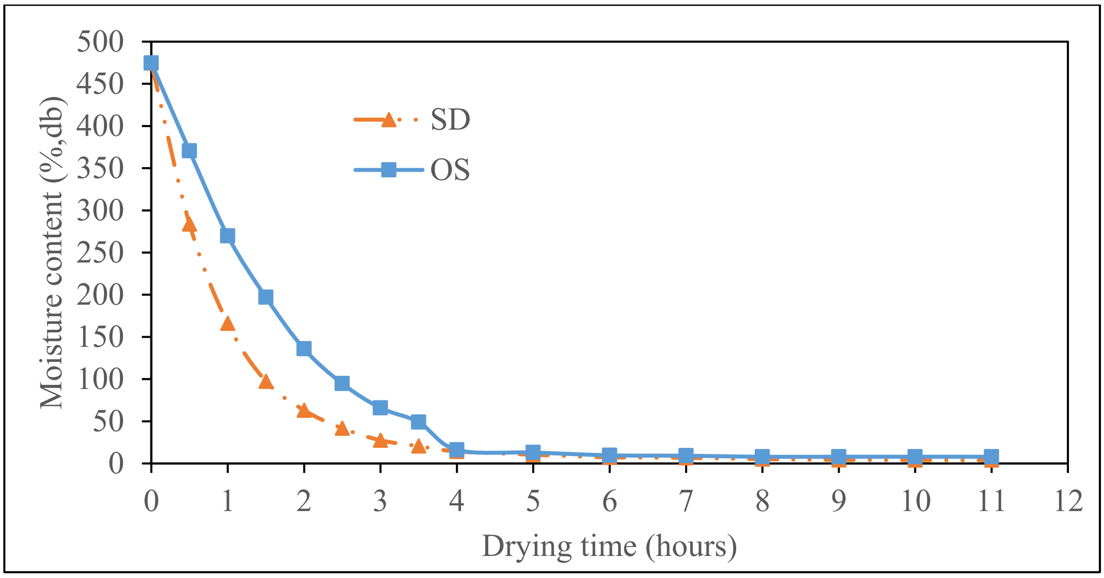

Figure 4.5: Drying curves of cowpeas in the solar tunnel dryer and open sun.

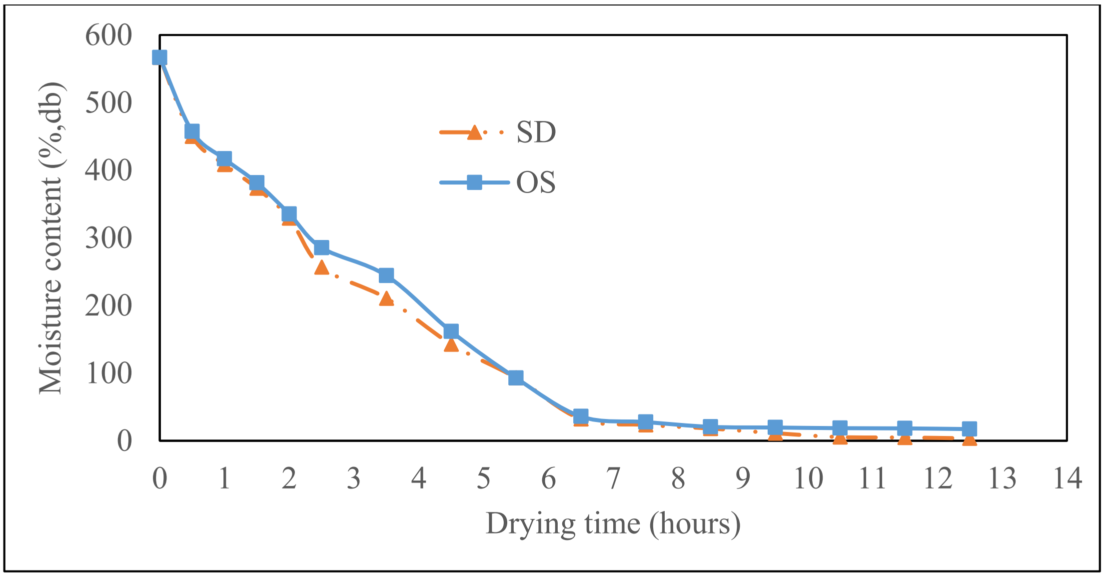

Figure 4.6: Drying curves of amaranth in the solar tunnel dryer and open sun.

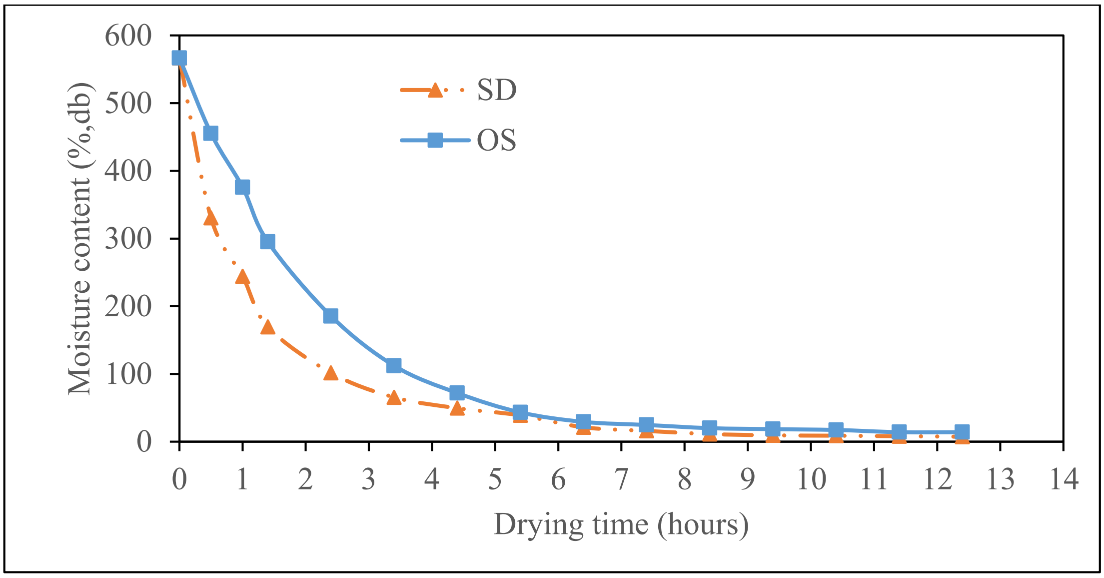

Figure 4.7: Drying curves of stinging nettle in the solar tunnel dryer and open sun.

4.3.2.2 Drying Rate

Table 4.7 presents the overall drying rates of the five vegetables in the solar tunnel dryer and open sun as calculated using Equation (2.2). The rates ranged from 39.42-72.99(g/g)/hr for the solar tunnel dryer and 39.25-71.71(g/g)/hr for open sun. Cabbages attained the lowest (39.42 g/g)/hr) drying rate while kales had the highest (72.99 g/g)/hr) and this trend was replicated in the open sun drying. The results further indicate that the overall drying rates for the solar tunnel dryer were slightly higher than the open sun. However, the t-test results, (kales p=0.980, cabbage p=0.461, cowpeas p=0.891, singing nettle p=0.978, amaranth p=0.652) indicate no significant difference in the drying rates of the solar tunnel dryer and the open sun for the five vegetables. Instantaneous drying curves show that drying rates for the vegetables in the initial stages were higher for the open sun compared to the solar tunnel dryer (Figures 4.8-

4.12). However, the rates for the later increased as drying progressed, due to higher air temperatures in the solar tunnel dryer. Further, the results show that after the removal of the surface moisture, drying rate decreases as the energy requirement to move the moisture from the internal part of the product is more. Similar observation were made by Papu, Sweta, Singh, Jaivir and Singh (2014) in greenhouse solar drying of amaranth leaves.

Table 4.7: Overall drying rates in the solar tunnel dryer and open sun

Vegetable	Solar tunnel dryer (g/g)/hr	Open sun (g/g)/hr
Kales	72.99	71.71
Cabbage	39.42	39.25
Cowpeas	58.85	58.33
Amaranth	44.85	43.95
Stinging nettle	69.92	69.08

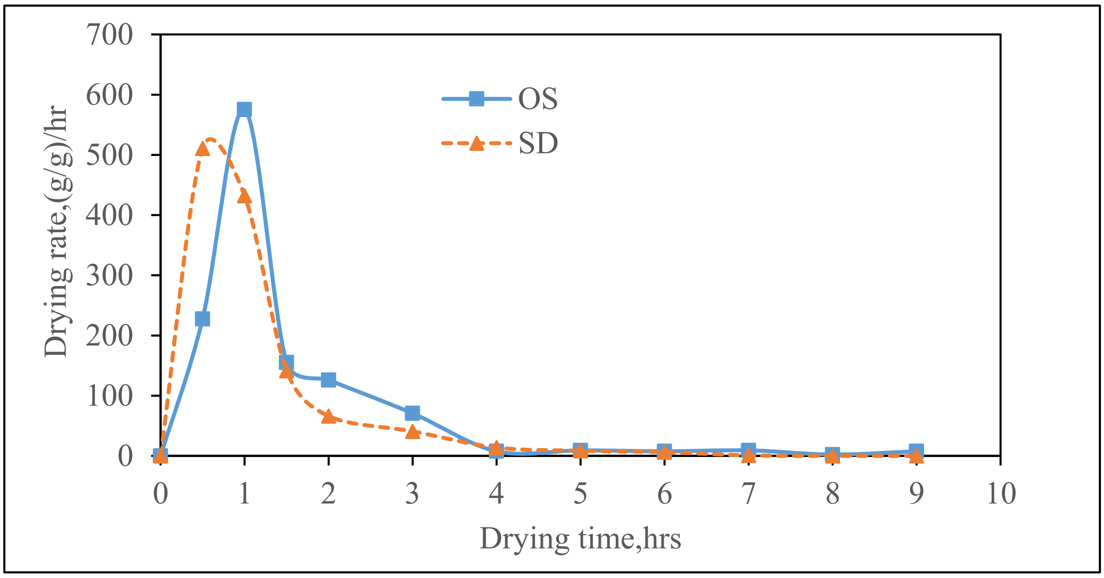

Figure 4.8: Drying rate curves of kales in solar tunnel dryer and open sun.

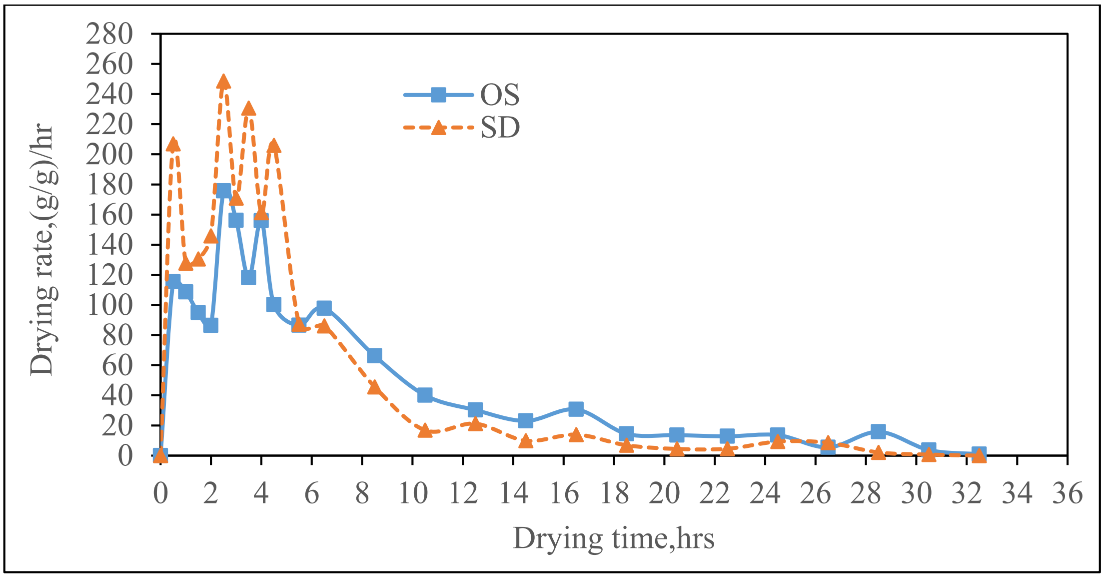

Figure 4.9: Drying rate curves of cabbage in solar tunnel dryer and open sun.

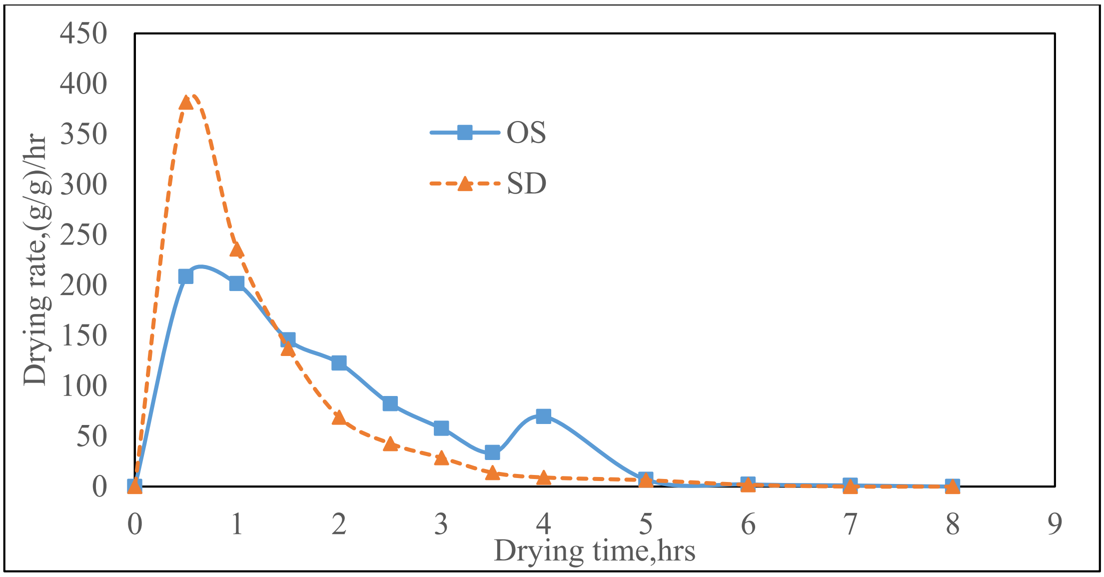

Figure 4.10: Drying rate curves of cowpeas in solar tunnel dryer and open sun.

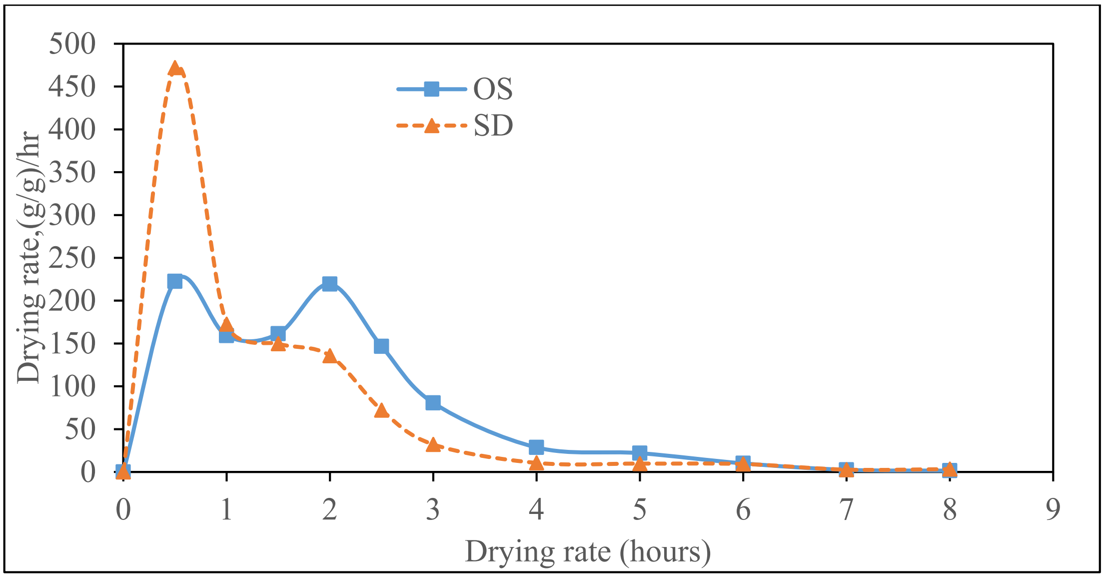

Figure 4.11: Drying rate curves of stinging nettle in solar tunnel dryer and open sun.

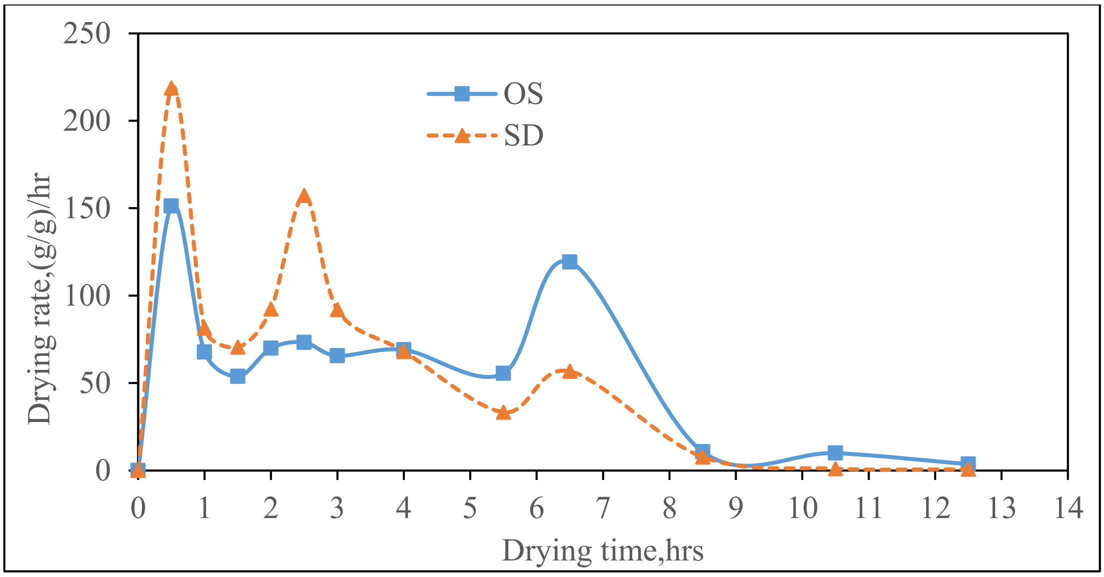

Figure 4.12: Drying rate curves of amaranth in solar tunnel dryer and open sun.

4.3.2.3 Effective Diffusivity

The effective moisture diffusivity (D_{eff}) values evaluated in the drying of the five vegetables dried by the solar dryer and in the open sun are summarised in Table 4.8.

These values were computed using Equation (2.13). The computed effective moisture diffusivity for each vegetable represents an overall mass transport property of moisture in the material, which include liquid diffusion, vapour diffusion or any other possible mass transfer mechanism. The values for the solar dried vegetables were found to be higher compared to those of the open sun drying for all the vegetables studied. The higher effective moisture diffusivity values obtained in the solar tunnel dryer were related to the higher temperatures attained meaning that the drying rate in the solar dryer were higher than the open sun. According to Sacilik and Elicin, (2006), temperature increase leads to increase in moisture removal from the dried product. At higher drying temperatures, the effective diffusivity is expected to be higher, especially with an increase in the drying air velocity (Togrul *et al.,* 2003; Park, Vohnikova & Brod, 2002).

Table 4.8: Comparison of effective moisture diffusivity for various vegetables when dried in the solar tunnel dryer and the open sun

Vegetable	Effective Moisture Diffusivity (m^2/s)	
	Solar dryer	Open sun
Kales	1.25×10^{-9}	1.04×10^{-9}
Cabbage	2.83×10^{-10}	2.09×10^{-10}
Cowpeas	8.78×10^{-10}	5.85×10^{-10}
Amaranth	6.63×10^{-10}	4.92×10^{-10}
Stinging nettle	3.46×10^{-10}	2.58×10^{-10}

The differences in values for D_{eff} of the vegetables may be attributed to the differences in nature and structure of the different materials. The values obtained for the five vegetables were within the general range of 10^{-9} to 10^{-11} m^2/s, which is typical of food materials and agricultural crops (Madamba, Driscoll & Buckle, 1996; Doulia, Tizia, & Gekas, 2000; Honoré, François, Raguilignaba, Aboubacar, & Hélène, 2014). Similar results have been reported for bay leaves and grasses (Demir *et al.,* 2004), laurel leaves (Yagcioglu *et al.,* 1999), kale leaves (Mwithiga and Olwal, 2005) and mint leaves (Doymaz, 2006).

4.3.2 Effect of Drying Method on Colour of the Vegetables

Table 4.9 shows the $L*$, $a*$, $b*$ and hue angle $h*$ values for kales, cabbage amaranth and stinging nettle leaves dried under the solar tunnel dryer and open sun. The hue angle $h*$ values were computed based on $L*$, $a*$ and $b*$ values using Equation (3.10). From the results the values of $L*$ for all the solar dried vegetables were slightly higher as compared to the open sun drying. Lower values of $a*$ were observed for all the solar dried vegetables while $b*$ values were slightly higher for kales, cabbage and amaranth in the solar dryer compared to the open sun drying. The results further indicate that the hue angles for the solar dried vegetables were higher than those of the open sun drying implying that the quality of the solar dried vegetables was better.

At 5% level of significance, Table 4.10-4.13 shows that there was significant difference (p-value, $3.41\text{x}10^{-06}$, $F_{crit,5\%}$, 4.494; $F_{computed}$, 47.965; p-value, 0.0104, $F_{crit,5\%}$, 4.494; $F_{computed}$, 8.412; p-value, 0.0015, $F_{crit,5\%}$, 4.494; $F_{computed}$, 14.725, p-value, 0.0407, $F_{crit,5\%}$, 4.414; $F_{computed}$, 4.862) for all the vegetables considered in hue angle between solar tunnel dryer and open sun. This indicates that the solar dried vegetables had less colour change, hence of better quality, compared to the open sun ones.

Table 4.9: Colour parameters for various vegetables dried using the solar tunnel dryer and open sun

	Fresh			Hue^0		Dry			Hue^0
	L*	a*	b*	h*		L*	a*	b*	h*
Kales	38.47	-12.46	13.71	132.28	SD*	28.57	-6.11	7.84	127.9
					OS**	29.5	-3.83	7.00	118.7
Cabbage	81.36	-7.53	18.07	112.62	SD	66.95	3.89	27.42	81.92
					OS	64.47	6.16	27.21	77.25
Amaranth	43.19	-11.39	18.32	122.32	SD	33.76	-4.05	13.24	107.01
					OS	30.02	-1.10	9.48	96.62
Stinging nettle	44.22	-15.23	21.31	125.55	SD	28.28	-3.14	8.94	109.37
					OS	27.98	-1.97	9.24	102.02

*Solar dryer, **Open sun

Table 4.10: Hue angle ANOVA results for kales dried in the solar dryer and open sun

Source of Variation	SS	df	MS	F	P-value	F crit
Drying condition	455.3434	1	455.3434	47.96515	3.41E^{-06}	4.493998
Residual	151.8914	16	9.493212			
Total	607.2348	17				

Table 4.11: Hue angle ANOVA results for cabbages dried in the solar dryer and open sun

Source of Variation	SS	df	MS	F	P-value	F crit
Drying condition	61.99254	1	61.99254	8.411543	0.010435	4.493998
Residual	117.919	16	7.369936			
Total	179.9115	17				

Table 4.12: Hue angle ANOVA results for amaranths dried in the solar dryer and open sun

Source of Variation	SS	df	MS	F	P-value	F crit
Drying condition	759.2006	1	759.2006	14.72529	0.001454	4.493998
Residual	824.9217	16	51.55761			
Total	1584.122	17				

Table 4.13: Hue angle ANOVA results for stinging nettle dried in the solar dryer and open sun

Source of Variation	SS	df	MS	F	P-value	F crit
Drying condition	115.6289	1	115.6289	4.861979	0.040702	4.413873
Residual	428.0808	18	23.78227			
Total	543.7097	19				

4.3.3 Effect of Drying Method on Ascorbic Acid Levels of the Vegetables

The results of the ascorbic acid levels/Vitamin C in the vegetables before and after drying in the solar dryer and open sun are presented in Table 4.14. The results reveal that the content of Vitamin C retention in the vegetables dried in both systems dropped significantly compared to the fresh ones. This was associated to heat damage during the drying process as was also reported by Giovanelli, Zanoni, Lavelli & Nani, (2002) where it was observed that the reduction in ascorbic acid content in drying of tomatoes slices was mainly due to the temperature, exposure to direct sun light and the presence of air (oxidation). Further studies by Gregory (1996) mentioned that the loss of ascorbic acid was primarily due to chemical degradation involving oxidation of ascorbic acid.

Table 4.14: Comparison of ascorbic* levels for solar dryer and open sun dried vegetables

	Ascorbic acid (mg/100g)		
Vegetable	Fresh	Solar dryer	Open sun
Kales	169.27	126.80	114.48
Cabbage	49.30	21.80	16.26
Amaranthus	86.10	33.15	31.69
Stinging nettle	93.83	32.74	22.40
Cowpeas	146.30	56.02	52.87

*Vitamin C

4.3.4 Effect of Drying Method on Ascorbic Acid Levels of the Vegetables

Table 4.15 presents the results of the beta carotene content in the vegetables before and after drying in the solar tunnel dryer and in the open sun. The results show that the retention of beta carotene in all the vegetables were higher for the solar tunnel drying than the open sun. This is consistent with findings of Nyambaka and Riley (2001) that solar drying of vegetables achieves higher retention of micronutrients than sun drying. However, ANOVA analysis (Table 4.16) indicates that there was no significant difference (p-value, 0.097, $F_{crit,5\%}$, 3.885; $F_{computed}$, 2.844) in the beta carotene levels for both methods of drying.

Table 4.15: Comparison of Beta carotene levels for fresh, solar dried and open sun vegetables

	Beta carotene (mg/100g)			Percentage retention	
Sample	Fresh	Solar dryer	Open sun	Solar dryer retention (%)	Open sun retention (%)
Kales	34.94	21.78	12.34	62	35
Amaranth	34.09	19.87	13.32	58	39
Cabbage	7.73	4.13	2.43	53	31
Stinging nettle	51.16	31.40	23.65	61	46
Cowpeas	67.51	42.60	23.56	63	35

Table 4.16: Beta carotene ANOVA results for solar dryer and open sun dried vegetables

Source of Variation	SS	df	MS	$F_{computed}$	P-value	$F_{critical}$
Drying condition	1475.332	2	737.6662	2.844172	0.097491	3.885294
Residual	3112.327	12	259.3606			
Total	4587.66	14				

4.3.5 Evaluation of Thin Layer Drying Models in Drying of High Moisture Content Vegetables in the Solar Tunnel Dryer

The thin layer drying models presented in Table 2.1 were evaluated using Excels 2007^{TM} in order to characterise the drying of various high moisture content vegetables for both the solar tunnel dryer and the open sun (Tables 4.17-4.21). The acceptability of the model to best characterise the drying of the vegetables was based on $R^2 \cong 1$, and low values RMSE and χ^2. All nine models showed good fit with R^2 ranging from 0.8859-0.994, χ^2 from 0.0245-0.00145, RMSE from 0.1372-0.0373 and ε(%) from 48.3±82.6-7.9±11.9 for all the vegetables. However, the Page model had the highest value of R^2 and the lowest values of χ^2, RMSE and ε(%) compared to the other eight models for kales, cabbage, cowpeas and amaranth. Accordingly, the Page model was selected to best characterise thin-layer drying of the above four vegetables, while the Verma *et al* model best characterised stinging nettle in the solar tunnel dryer. Similar results for the Page model have been reported during thin layer drying studies of chili, Tunde-Akintunde, (2011) and Doymaz *et al.,* (2002) and rapeseed, Duc, Han and Keum, (2011), among others. Tables 4.17-4.21 further presents the mean absolute residual errors and the corresponding standard deviations for the drying models. From the results, the Page model attained the lowest mean residual error values 8.8±5.5, 12.3±24.2, 27.3±34.6 and 7.9±11.9 for kales, cabbages, cowpeas, and amaranth while Verma *et al* model attained 11.9±19.1 for stinging nettle. Higher prediction performances (53.8-76.0%) based on a ±10% residual error interval achieved by the two models further confirms their superiority in predicting thin layer drying of the vegetables in a solar tunnel dryer. The lower corresponding standard deviations illustrate uniformity in prediction level of these models when drying in the solar tunnel dryer (Kanali, 1997).

Table 4.17: Estimated parameters and comparison criteria of moisture ratio for various models in drying of kales in the solar tunnel dryer

Model	Model constants and coefficients									R^2	χ^2	RMSE	ε(%)	η_p(%)
	k	k_0	k_1	a	b	c	h	n	g					
Newton	0.2787									0.94277	0.00747	0.08273	21.9±15.1	16.7
Page	0.2489							1.1428		0.98645	0.00194	0.0402	8.8±5.5	66.7
Henderson	0.313			1.0912						0.94702	0.00659	0.07413	20.9±17.5	41.7
garithmic	0.3372			1.0626		0.0364				0.94786	0.00716	0.0733	17.4±13.3	33.3
Diffusion	0.2787			1	1					0.94277	0.00913	0.07165	20.0±15.1	33.3
Two Term		0.313	0.313	0.5456	0.5456					0.94702	0.00824	0.07413	20.9±17.5	41.7
Two term exponential	0.6661			0.9999						0.94277	0.00821	0.08273	20.0±15.1	41.7
Verma	0.6661			16.5917					0.7114	0.97255	0.00522	0.06256	24.5±32.9	58.3
Modified Henderson	0.313			0.3637			0.313		0.313	0.94702	0.01099	0.07413	20.9±17.5	41.7

Table 4.18: Estimated parameters and comparison criteria of moisture ratio for various models in drying of cabbage in the solar tunnel dryer

Model	Model constants and coefficients									R^2	χ^2	RMSE	ε(%)	η_p(%)
	k	k_0	k_1	a	b	c	h	n	g					
Newton	0.0389									0.94351	0.00945	0.11906	33.2±71.8	56.0
Page	0.0028							1.8897		0.98699	0.00145	0.04559	12.3±24.2	76.0
Henderson	0.0449			1.0931						0.9337	0.007	0.1003	28.2±62.6	60.0
Logarithmic	0.0449			1.0931		0				0.9337	0.00732	0.1003	28.2±62.6	64.0
Diffusion	0.0389			0.9999	1					0.94351	0.01031	0.11906	33.2±71.8	56.0
Two Term		0.0449	0.4491	0.5456	0.4178					0.9337	0.00767	0.1003	28.2±62.6	64.0
Two term exponential	0.039			1						0.94351	0.00986	0.11906	33.2±71.8	56.0
Verma	0.0951			24.5246					0.0994	0.97574	0.0027	0.06088	17.7±40.2	76.0
Modified Henderson	0.0449			0.3644		0.3644	0.0449		0.0449	0.9337	0.00847	0.1003	28.2±62.6	60.0

Table 4.19: Estimated parameters and comparison criteria of moisture ratio for various models in drying of cowpeas in the solar tunnel dryer

Model	Model constants and coefficients									R^2	χ^2	RMSE	ε(%)	η_p(%)
	k	k_0	k_1	a	b	c	h	n	g					
Newton	0.2698									0.94351	0.00945	0.11906	33.2±71.8	30.8
Page	0.1026							1.8848		0.98699	0.00145	0.04559	12.3±24.2	53.8
Henderson	0.3082			1.1154						0.9337	0.007	0.1003	28.2±62.6	38.5
Logarithmic	0.3082			1.1154		0				0.9337	0.00732	0.1003	28.2±62.6	38.5
Diffusion	0.2698			1	1					0.955	0.0111	0.0831	43.2±56.9	30.8
Two Term		0.3082	0.3082	0.5577	0.5577					0.952	0.0091	0.0717	32.6±47.4	38.5
Two term exponential	0.4046			0.9999						0.926	0.026	0.1338	33.0±19.0	7.7
Verma	0.5881			4.3067					0.7982	0.984	0.0028	0.0417	32.7±41.6	53.8
Modified Henderson	0.3082			0.3718		0.3718	0.3082		0.3082	0.952	0.0118	0.0717	32.2±47.4	38.5

Table 4.20: Estimated parameters and comparison criteria of moisture ratio for various models in drying of amaranth in the solar tunnel dryer

Model	Model constants and coefficients									R^2	χ^2	RMSE	ε(%)	η_p(%)
	k	k_0	k_1	a	b	c	h	n	g					
Newton	0.1077									0.9047	0.0204	0.1372	48.1±82.6	23.1
Page	0.0086							2.3455		0.9845	0.0022	0.0385	7.9±11.9	69.2
Henderson	0.1318			1.1389						0.8859	0.0159	0.1046	39.1±64.9	30.8
Logarithmic	0.1318			1.139		0				0.8859	0.0175	0.1046	39.1±64.9	30.8
Diffusion	0.1077			1	1					0.9047	0.0245	0.1237	48.3±82.6	23.1
Two Term		0.1318	0.1318	0.5695	0.5695					0.8859	0.0195	0.1046	39.1±64.9	30.8
Two term exponential	0.1077			1						0.9047	0.0223	0.1237	48.1±82.6	23.1
Verma	0.3029			23.8					0.32	0.9659	0.0053	0.0574	17.0±24.3	53.8
Modified Henderson	0.1318			0.3797		0.3797	0.3118		0.3118	0.8859	0.025	0.1046	39.1±64.9	30.8

Table 4.21: Estimated parameters and comparison criteria of moisture ratio for various models in drying of stinging nettle in the solar tunnel dryer

Model	Model constants and coefficients									R2	χ2	RMSE	ε(%)	η_p(%)
	k	k_0	k_1	a	b	c	h	n	g					
Newton	0.2222									0.965	0.00851	0.08834	25.3±28.3	30.8
Page	0.1006							1.6325		0.990	0.00172	0.03787	15.8±28.4	69.2
Henderson	0.2583			1.1217						0.961	0.0059	0.07011	17.9±20.5	38.5
Logarithmic	0.2583			1.1217		0				0.961	0.00655	0.07011	17.9±20.5	38.5
Diffusion	0.2222			1	1					0.965	0.01041	0.08834	25.3±28.3	30.8
Two Term		0.2583	0.2583	0.5608	0.5608					0.961	0.00737	0.07011	17.9±20.5	38.5
Two term exponential	0.2223			0.9999						0.965	0.00937	0.08834	25.3±28.3	30.8
Verma	0.4009			1.9282					0.9657	0.994	0.00112	0.02899	11.9±19.1	69.2
Modified Henderson	0.2583			0.3738		0.3789	0.2583		0.2583	0.961	0.00983	0.07011	17.9±20.5	30.8

Comparisons of the moisture ratios predicted by the Page and Verma *et al* models and the actual values for the solar tunnel dryer are shown in Figures 4.13-4.17. The results show very limited variation from the actual, thus further confirming the suitability of the models. These observations confirm that the Page and Verma model are the best models for predicting the drying of kales, cabbage, cowpeas, amaranth and stinging nettle vegetables in the tunnel solar dryer.

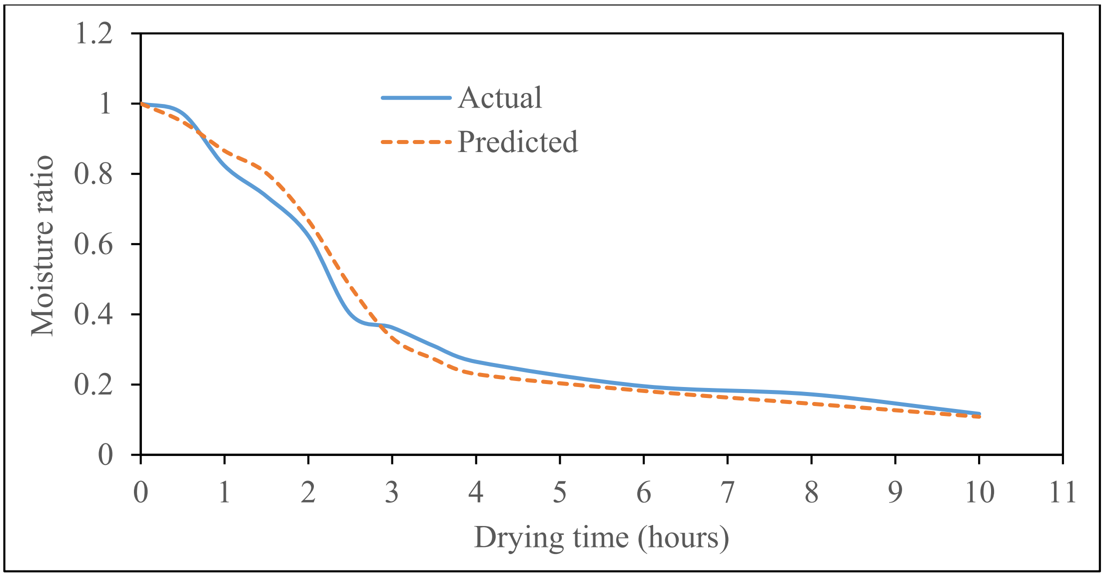

Figure 4.13: Comparison between predicted and actual moisture ratios using the Page model in drying of kales.

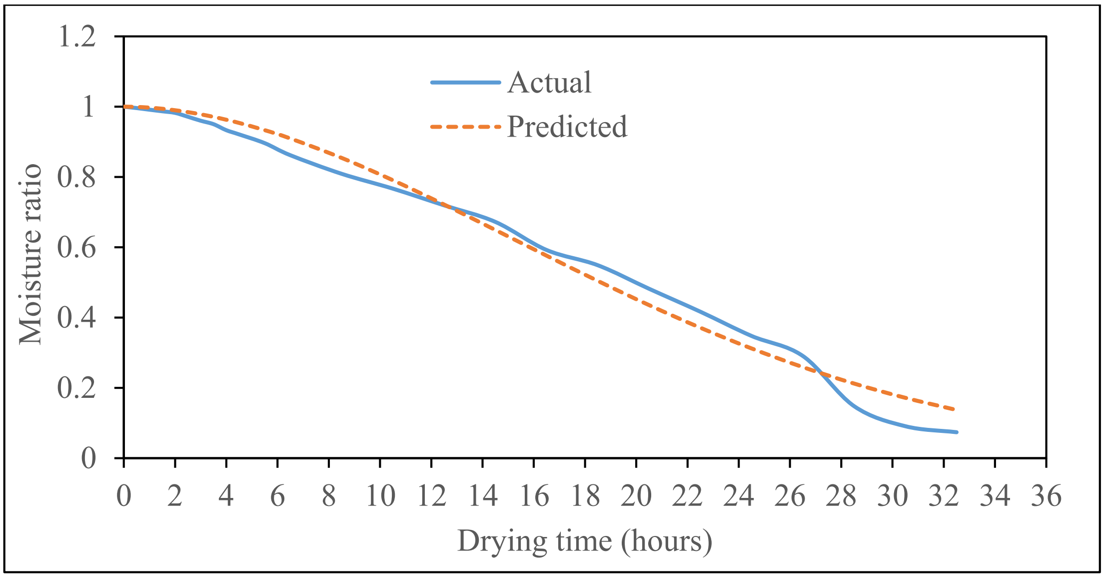

Figure 4.14: Comparison between predicted and actual moisture ratios using the Page model in drying of cabbages.

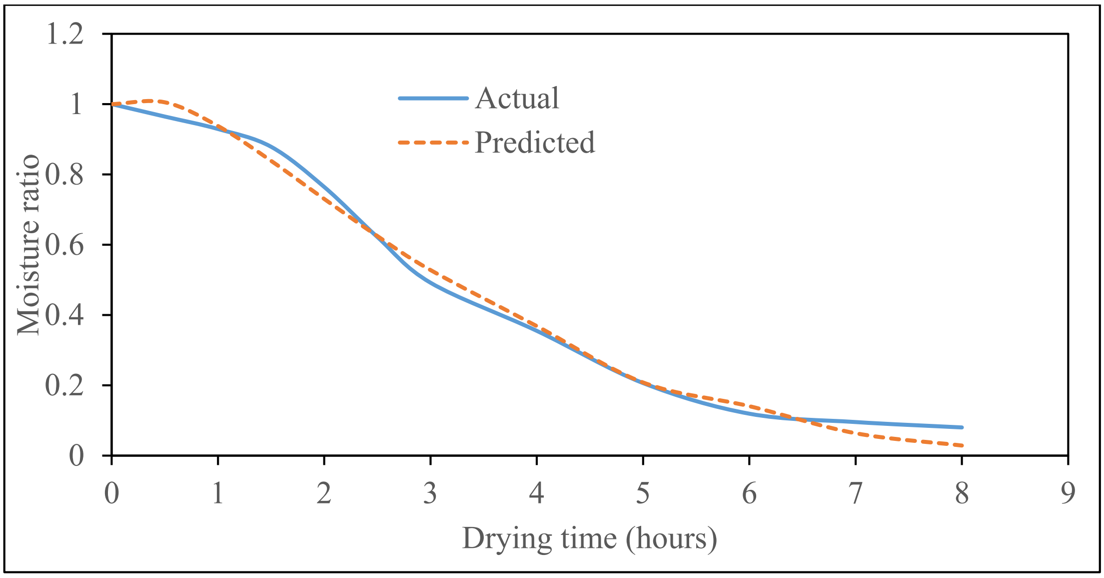

Figure 4.15: Comparison between predicted and actual moisture ratios using the Verma *et al* model in drying of stinging nettle.

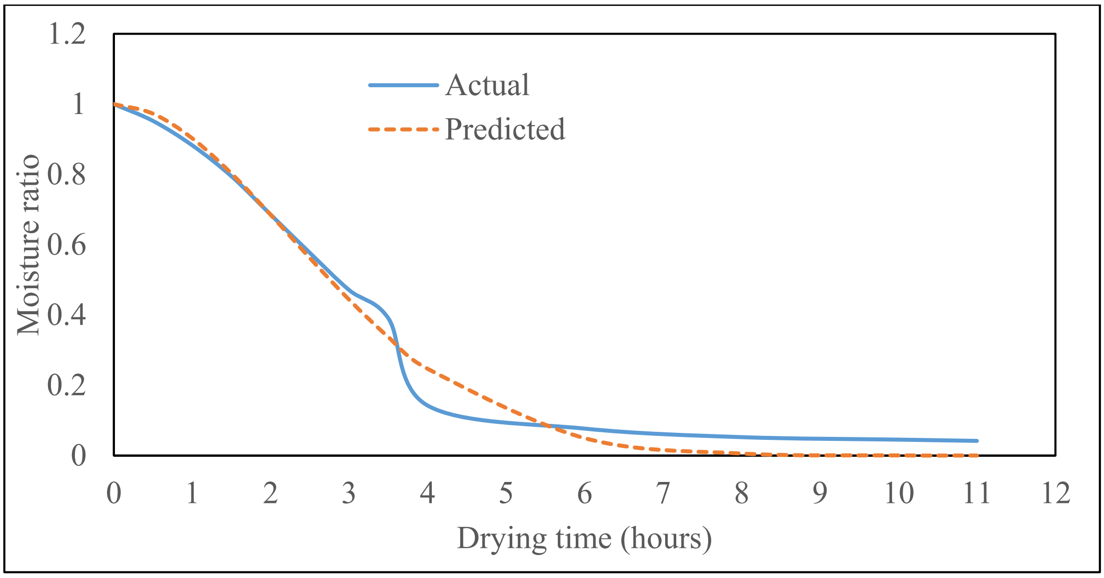

Figure 4.16: Comparison between predicted and actual moisture ratios using the Page model in drying of cowpeas.

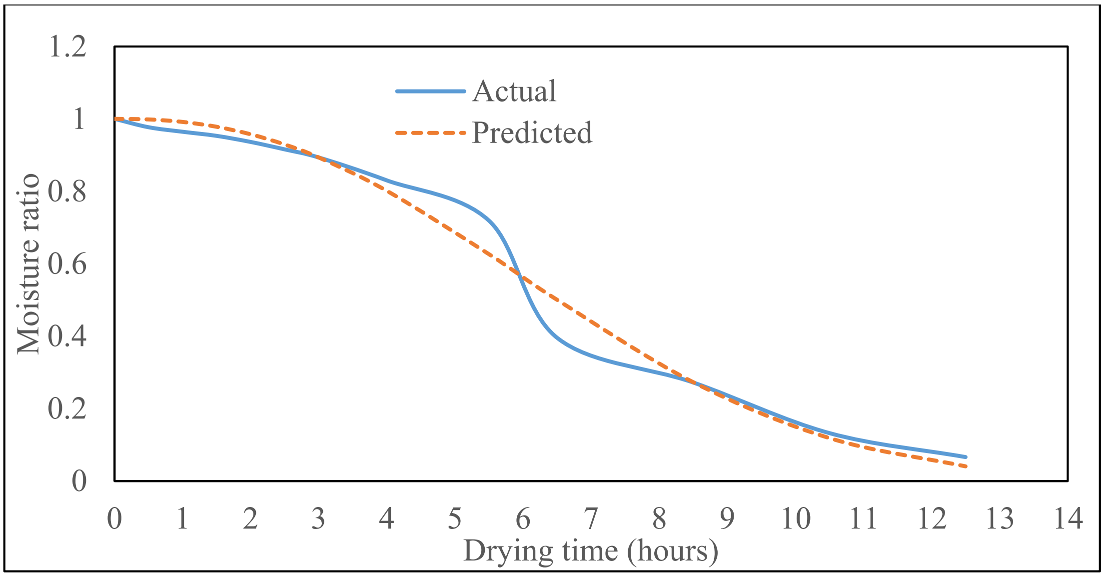

Figure 4.17: Comparison between predicted and actual moisture ratios using the Page model in drying of amaranth.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study was carried out with the main objective being to evaluate thin layer drying characteristics of high moisture content vegetables in a modified solar tunnel dryer. The results indicate that the dryer can be used effectively for thin layer drying of high moisture content vegetables. From the study it was established that:

There was no significant difference in collector temperatures between the modified and unmodified solar tunnel dryer, although the mean temperatures were slightly higher in the modified (45.1±9.1^{o}C) than the unmodified (45.5±8.9^{o}C) dryer. The dryer temperatures were found to be significantly higher than the prevailing ambient temperatures at 5% level of significance. On the other hand, the relative humidity for both dryers were found not to be significantly different ($p>0.05$), although it was slightly lower for the modified (16.3±8.8%) than for the unmodified (17.9±10.5%) dryer.

The modified solar tunnel dryer was able to dry the vegetables from initial moisture contents of 1288.9, 669.2, 474.7, 566.7, and 566.7% to final moisture content of 7.57, 10.41, 5.05, 7.29 and 3.55 (dry basis) for cabbages, kales, stinging nettle, amaranth and cowpeas, respectively, within 14 hours while open sun drying took longer to attain the similar moisture content levels. However, cabbages took more than 30 hours for the moisture content to reduce from 1288.9% to less than 12%. There was significant difference ($p>0.05$) in hue angle between solar dryer and open sun dried vegetables. This indicates that vegetables dried using the solar tunnel dryer had less colour change, hence of better quality compared to those dried in the open sun. Finally, the results show that there was high and significant ($p>0.05$) retention of both Vitamin C and beta carotene in the vegetables dried in the solar dryer as compared to the open sun drying.

All the nine thin layer drying models evaluated can be used to characterise the drying of high moisture content vegetables since the coefficients of determination R^2, achieved were high ranging from 0.886-0.994, while the χ^2 and RMSE were low ranging from 0.0012-0.0022 and from 0.02899-0.04559, respectively. The Page and Verma *et al* models were found to best characterise the drying of the vegetables as they attained higher R^2 (0.985-0.994) and lower χ^2 (0.00112-0.00220) and RMSE (0.02899-0.04559) values. In addition the low mean residual errors (7.9±11.9-27.3±34.6) and higher prediction performances (53.8-76.0%) based on a ±10% residual error interval achieved by the two models further confirms their superiority in predicting thin layer drying of the vegetables in a solar tunnel dryer.

5.2 Recommendations

The following key areas were identified and recommended for further studies:

1. There is need for laboratory colour tracking as drying progresses for each vegetable in order to establish colour change with change in moisture content.
2. Examining the effect of leaf surface area to drying rates of the vegetables.

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APPENDICES

Appendix A 1: Solar tunnel dryer air condition data

Table A 1: Temperature, relative humidity and solar radiation data for 24th Feb 2015

Time	Ta (°C)	Ti (°C)	To (°C)	RHa (%)	RHi (%)	RHo (%)	S.R (W/m²)
10:05 AM	25.09	27.09	30.27	46.4	44.1	35.9	740.6
10:30 AM	27.11	29.67	33	43.8	39	31.6	828.1
11:00 AM	27.97	34.2	37.92	39.3	32.6	25.7	944.4
11:30 AM	30.04	38.23	42.65	36.9	27.5	20.7	996.9
12:00 PM	28.99	41.53	44.94	33.8	21.4	17	1,063.1
12:30 PM	30.93	46.1	47.06	32.9	16.9	14.7	1,041.9
1:00 PM	31.46	50.34	50.82	30.8	13.5	12.2	1,076.9
1:30 PM	33.18	53.33	52.67	27.9	12	11	1,059.4
2:00 PM	33.94	55.6	54.3	25.5	10.2	9.5	1,020.6
2:30 PM	32.15	57.38	56.11	26.6	9	8.1	968.1
3:00 PM	34.23	58.57	56.94	25.1	8.5	7.6	834.4
3:30 PM	33.05	58.49	56.7	24.6	8.6	7.5	753.1
4:00 PM	33.37	57.06	55.44	25.6	8.8	7.9	653.1
4:30 PM	33.52	55.52	54.15	25.2	9	8	531.9
5:00 PM	31.71	53.07	51.81	27.7	10	9.1	400.6
Mean	31.12	47.75	48.32	31.47	18.07	15.10	860.87
Stdev	2.75	10.92	8.77	7.18	12.08	9.30	209.31

In the table Ta, Ti, To and RHa, RHi, RHo are ambient, inlet and outlet temperatures and relative humidity while S.R is solar radiation

Table A 2: Temperature, relative humidity and solar radiation data for 25th Feb 2015

Time	Ta (°C)	Ti (°C)	To (°C)	RHa (%)	RHi (%)	Rho (%)	S.R (W/m²)
10:05 AM	25.14	27.53	30.19	45.2	34.7	40.2	710.6
10:30 AM	26.43	30.82	33.63	39.3	26.8	31.9	836.9
11:00 AM	26.87	34.6	36.69	35.4	21.1	24.8	928.1
11:30 AM	28.39	38.03	39.43	33.6	18	20.6	1,003.1
12:00 PM	30.82	42.06	42.18	29.4	15.5	16.2	1,069.4
12:30 PM	31.33	45.37	44.69	28.4	13.7	14.3	1,084.4
1:00 PM	29.97	48.84	47.88	27.9	10.3	10.3	1,083.1
1:30 PM	33.97	51.38	49.48	24.3	9.2	9.2	1,074.4
2:00 PM	32.51	51.99	50.13	21.9	7.5	7.6	1,018.1
2:30 PM	34.12	53.63	51.35	18	6.2	6.3	949.4
3:00 PM	34.57	53.55	51.88	16.8	5.3	5.5	913.1
3:30 PM	34.55	54.26	53.04	13.9	3.9	4.1	814.4
4:00 PM	34.23	53.89	52.75	14.8	4.6	4.9	699.4
4:30 PM	33.89	52.75	51.77	14.2	4.1	4.6	586.9
5:00 PM	33.02	52.42	51.49	15.3	4.5	4.4	568.1
Mean	31.32	46.07	45.77	25.23	12.36	13.66	889.29
Stdev	3.25	9.21	7.57	9.99	9.32	11.15	178.99

Table A 3: Temperature, Relative humidity and Solar radiation data for 26th Feb 2015

Time	Ta (°C)	Ti (°C)	To (°C)	RHa (%)	RHi (%)	RHo (%)	S.R (W/m²)
10:05 AM	26.16	28.35	33.7	48	49.7	37.6	651.9
10:30 AM	27.48	31.56	36.91	45.2	40	29.6	734.4
11:00 AM	29.34	34.84	39.91	36.3	32.5	24.8	866.9
11:30 AM	28.22	37.78	41.77	37.4	26.9	21.6	899.4
12:00 PM	29.64	40.92	44.01	36.2	23.3	19.3	985.6
12:30 PM	29.64	43.65	45.37	38	21.4	19	955.6
1:00 PM	30.87	46.74	47.61	38.6	18.4	17.1	958.1
1:30 PM	31	48.8	49.28	37.2	16.5	15.8	988.1
2:00 PM	32.56	51	51.14	32.6	14	13.8	990.6
2:30 PM	33.57	52.24	51.31	29.9	12.6	12.8	919.4
3:00 PM	32.12	51.14	49.38	33.2	13.1	13.7	293.1
3:30 PM	29.84	47.78	44.6	34.8	16	16.5	228.1
4:00 PM	29.24	44.6	42.09	34.8	16.9	17.9	229.4
4:30 PM	28.67	41.24	38.76	36.1	22.1	21	121.9
5:00 PM	28.07	38.14	35.93	37.2	23.6	23.1	115.6
Mean	29.76	42.59	43.45	37.03	23.13	20.24	662.54
Stdev	2.00	7.35	5.65	4.53	10.51	6.61	355.03

Appendix A 2: Publications

Kamwere, M.M., Kanali, C.L., Mutwiwa, U.N., Kituu, G.M. (2015). Thin layer drying characteristics of stinging nettle (*urticadioica l.*) in a solar tunnel dryer. International Journal of Engineering Research & Technology (IJERT), Vol. 4 Issue 12, pg. 428-434. Journal homepage: www.ijert.org