MODELLING OF DRYING KINETICS AND QUALITY CHARACTERISTICS OF SOLAR DRIED BEEF

by

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DECLARATION

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

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DEDICATION

I dedicate this PhD thesis to my parents Mr. Boniface Mewa Barasa and Mrs. Seline Awino Asola for their outstanding love, prayers and support throughout my educational journey, to my loving husband, Kenneth Omondi Owuocha for his constant encouragement and support and to my beautiful daughters Valencia Atieno Owuocha and Arianna Hawi Owuocha for their invaluable love and patience.

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GENERAL ABSTRACT

Beef is highly perishable and its commercialization in the arid and semi-arid areas of Kenya is a challenge. Sun drying has always been used to preserve meat in these areas. However, there is a need to focus attention on improvement of quality of the drying process. This can be achieved through drying modelling and simulation as well as dried product quality characterization. This work aimed at investigating the solar tunnel dryer performance for dehydration of beef in one of the pastoral areas in Kenya. In this regard, appropriate models were used to establish beef desorption isotherms. Drying characteristics of fresh beef under controlled conditions (in a laboratory simulation dryer) were determined and related to drying kinetics under the varying atmospheric conditions (in a solar tunnel dryer). Assessment of mathematical models was done and moisture diffusivities established. The effect of drying methods on beef quality parameters as well as storage time and packaging type effects on solar dried beef samples were also determined. Laboratory analyses of the dried beef samples were done using standard procedures.

The desorption isotherms of beef were sigmoid shaped, type II isotherms. There was a decrease in equilibrium moisture content (EMC) with temperature increase at constant water activity, an increase in EMC with increased water activity at constant temperature and a decrease in net isosteric heat of sorption with increased moisture content. The GAB and Oswin models fit desorption data best. Drying rates and drying times were lower for thicker beef slices and increased at higher temperatures in the cabinet dryer, whereas effective moisture diffusivity (D_{eff}) was high at higher temperatures and increased sample thickness. There was a significant decrease ($P \leq 0.05$) in L^*, a^*, $b^*$and chroma/C^* colour values with increased temperature and beef thickness. At 60 °C, the rehydration ratio (RR) of beef slices increased whereas the firmness

decreased. Microbial numbers in beef dried at 30 °C and 40 °C were higher than that of fresh beef, whereas drying at 60 °C significantly ($p \leq 0.05$) reduced the microbial load.

The temperature profile along the drying chamber of the solar tunnel dryer increased with increased solar radiation and decreased continuously at high moisture content of beef. Whereas the beef drying processes occurred in the falling rate period, the drying rate was higher in the solar drier compared to open sun drying. The best prediction of beef drying characteristics was given by the Page model. Effective moisture diffusivity for the sun and solar dried samples varied from 1.775×10^{-10} to $2.282\ 10^{-10}\ m^2/s$. The L* and C* colour parameters, moisture content (%) and adhesiveness of solar dried samples were lower while RR, hardness (N), firmness (N), springiness (%) resilience and sensory scores were higher compared to sun dried beef. During storage, samples dried towards the centre of the drying chamber of the tunnel dryer were more stable to moisture changes, whereas those dried close to the ends were stable to microbial growth and fat oxidation. Deteriorative changes in dried beef during storage in Glass jars and aluminium foil packaging were significantly lower ($p \leq 0.05$) compared to polyethylene and paper.

CHAPTER 1: GENERAL INTRODUCTION

1.1. BACKGROUND INFORMATION

In the developing countries, there has been a constant rise in annual per capita meat consumption: From 10 kg to 26 kg in 1960 and 2000 respectively (Heinz and Hautzinger, 2007). This is due to an increase in population growth and disposable income (FAO, 2010). On the other hand, a significant portion of meat and meat products are wasted every year as a result of spoilage (FAO, 2001). In hot countries, meat preservation is quite a challenge due to its very high perishability. Moreover, in the absence of cold chain its commercialization mostly follows a rapid flow of fresh meat making the storage of excess meat, to be used during shortages impossible (FAO, 2001). Some traditional conservation techniques have been used to overcome this problem. These include, open sun drying, whereby meat is placed directly on the ground or spread on racks or mats. The drying process sometimes includes pre-processes like dry salting or brining, which enhance the capability of drying and reduces the products water activity to low values within a shorter time (Clemente *et al*., 2007).

For thousands of years, sun drying has been practiced; mainly by pastoralists and nomads with the aim of preserving meat during excess supply (Heinz, 1995). However, compared to sun drying, solar drying can speed up the drying process and improve dried product quality in terms of cleanliness, hygiene, appearance and taste (Sacilik, 2007). Numerous tests in the different regions have shown that fruits (Schirmer, *et.al,* 1996; Bala *et al.*, 2003; Elicin and Sacilik, 2005), vegetables (Sacilik, 2007; Sacilik *et al.*, 2006; Hossain and Bala, 2007) and fish (Bala and Mondol, 2001; Kituu *et al.*, 2010) can sufficiently be dried in a solar tunnel dryer. One major advantage of this dryer is that regulation of temperature is possible and the evaporated moisture can be removed by the air flow provided by a fan, thus increasing the products' drying rate. This work aimed at investigating the solar tunnel dryer's performance for meat dehydration in one of the pastoral regions of Kenya.

Drying is a complex process involving the transfer of heat and resulting in a direct transfer of moisture from some substance to the air (Yilbas *et al*., 2003). Generally, simulation and theoretical information about the behaviour of each product during removal of moisture are important for the study of drying systems, development of drying equipment, optimization and evaluation of commercial viability (Corrêa *et al*., 2007). Basically modelling is the use of a set of equations designed for describing the drying system as accurately as possible (Doymaz, 2014). The use of mathematical models for describing the dehydration processes of various agricultural products has been done (Akpinar *et al.,* 2003; Doymaz, 2004; Akgun and Doymaz, 2005; Trujillo *et al.,* 2007). In this work, appropriate models were used to establish meat desorption isotherms that related EMC to the critical water activity for safe drying of meat. Modelling of drying kinetics of meat under controlled conditions was done in a cabinet dryer with the aim of simulating drying kinetics in a solar tunnel dryer (with varying atmospheric conditions).

The quality of foods refers to its safety, sensory and nutritional properties. In many cases severe drying generally results in increased food safety but higher nutritional loss. Therefore, to ensure the desired quality of dried food products is obtained, the right temperature and an optimal drying time must be established (Maskan *et al*., 2002). Studies done on beef drying kinetics have mostly focused on modelling of the drying kinetics and influence of the drying air parameters on the heat and mass transfer characteristics (Gou *et al*., 2003, 2004; Trujillo *et al*., 2007; Clemente *et al*., 2009, 2011). However, reports on the quality changes on beef during drying are scanty. The present study was also done in order to determine the changes in beef quality during drying in a laboratory cabinet dryer so as to optimize beef quality in a solar tunnel dryer. However, deteriorative changes occur on meat not only during preparation and drying but also during storage, eventually affecting the dried product's quality characteristics. Appropriate packaging is therefore needed to ensure minimal change in product quality during storage. The effects of storage time and packaging type on the quality parameters of solar dried beef were also established.

1.2. MEAT

1.2.1. Production and consumption trends

Currently, the livestock sector of developing countries is one of the fastest growing sectors, with its share of GDP at 33% and is quickly increasing (Thornton, 2010). More than 50% of the livestock population in Kenya is found in the arid and semi-arid lands under pastoral production systems (Kahi *et al.,* 2006). Red meat in Kenya accounts for over 80 per cent of all the meat and is derived mainly from cattle, sheep, goats and camels (Gichure *et al.,* 2014). Indigenous cattle meats are among the main agricultural commodities with a potential in terms of economic growth, food security, poverty reduction and creation of employment (FAOSTAT, 2016). The consumption of meat in the developing nations is projected to keep rising until 2050, which is as a result of increased population growth and rising income (FAO, 2009). In sub-Saharan Africa, the most consumed meat product is beef. Its consumption in 2015 was 4.3 million tons, but by 2050 it is estimated to reach 13.5 million tons in this region. In Kenya, for example, it represented 73% of the total meat consumed in 2010 (FAOSTAT, 2016).

1.2.2. Structure and composition of meat

According to the definition of CFDAR, (1990), meat is the edible portion of the skeletal muscle of an animal that was healthy at the time of slaughter. Conveniently, meat can be regarded as the post mortem aspects of muscles, since the edible flesh of animal carcasses predominantly comprises of muscular tissue, (Lawrie, 1995). Generally, meat is made up of four major chemical components; water, proteins, lipids and carbohydrates and several other minor components including enzymes, vitamins, flavour components and pigments. Generally, the structure and chemistry of the muscle determines the main eating quality attributes in meat, for which consumers value the commodity. These include; colour, texture (tenderness and juiciness) and flavour (Castro-Giraldez *et al*., 2010). However, due to the intrinsic properties of fresh meat like availability of proteins, lipids and carbohydrate (glycogen) relatively high water activity (aw) and slightly acidic pH (Ayanwale *et al.*, 2007), its deterioration takes place progressively; from slaughter until consumption. This deterioration is mostly caused by microbial spoilage, enzyme activity and fat oxidation (Dave and Ghaly, 2011). In order to avoid the associated spoilage of meat, it is either cooked or processed into other forms so as to improve its shelf life (Olaoye *et al*., 2010; Olaoye and Onilude, 2010).

1.2.3. Preservation of meat in the tropics

A few hours after the onset of rigor-mortis and post-mortem handling, meat spoilage begins. This is mainly as a result of the hot environment of the tropics. The diverse nutrient composition also makes meat an ideal environment for a number of microorganisms (bacteria, yeasts and moulds) some of them being pathogens (Jay *et al.*, 2005). Meat preservation therefore, creates the avenue for maintaining its quality and safety (Dave and Ghaly, 2011). There are several interrelated factors that affect the keeping quality and shelf life of meat. These include; holding temperature, moisture content, endogenous enzymes, atmospheric oxygen, light and of utmost significance, micro-organisms (Zhou *et al*., 2010). The principles of meat preservation are mainly concerned with preventing or delaying microbial spoilage, autolysis and oxidative changes, which prevents deteriorative changes in taste, colour or texture (Ayanwale *et al.,* 2007). Methods of meat preservation include the use of high or low temperature treatments, reduction of water activity (a_w) or use of chemical preservatives. Water activity basically measures the amount of water that is available of for biological reactions including microbial growth. Bacteria, yeasts, moulds require water activity values of at least 0.91, 0.88 and 0.80 respectively for their growth. Therefore, reduction of water activity must be done to below these levels during meat preservation.

There are many methods of meat preservation including; drying, salting and curing, refrigeration and freezing and incorporation of additives, (FAO, 2007). However, the main preservation techniques in pastoral/ nomadic regions of Africa are sun-drying, salting, fermentation and deep frying (Heinz and Hautzinger, 2007). Moreover, meat drying still remains the most practical way of meat preservation in developing countries where warm climates and the absence of a cold storage are the prevailing conditions (Heinz, 1995).

1.3. DRYING OF MEAT

The practice of meat drying dates back to thousands of years ago. Traditionally dried intermediate moisture foods are those that contain a_w values in the range of 0.60 to 0.85 and moisture contents between 15 and 50%, whereas low moisture foods contain less than 25%

moisture and have water activity values between 0.00 and 0.60 (Jay *et al.*, 2005). The major attribute of meat drying is the ability to decrease its moisture content and thus lower the product's water activity. This ensures that a number of the moisture-mediated deteriorative reactions are minimized and the growth and reproduction of microorganisms inhibited (Duan *et al*., 2004). The advantages of dried products include; shelf stability, quality enhancement, less storage space, ease of transport and handling, convenience, further processing and useful in natural disasters including floods, earthquakes and cyclones. Dried meat products essentially can play a major role in providing protein rich foods to people in developing nations and have captured more attention since refrigeration is not needed throughout the transportation, marketing and storage periods (Mishra *et al.*, 2017).

Muscle meat of almost any kind can be dried, but the use of lean meat is essential since fat oxidation occurs during the drying process resulting in development of rancid flavours. Generally, unlike grains which are normally dried in dryers, deep beds, or bins, a number of other food products, including sliced fruits, vegetables, and meat are better dried in thin layers (Visavale, 2012). Drying is basically an operation involving combined and simultaneous heat and mass transfer processes in which energy must be applied. The thermal drying process involves removal of moisture from the meat, which is initiated through application of heat energy.

1.3.1. Moisture loss during drying

Moisture that is found in meat can be categorised into bound and free (or unbound) moisture. The movement of free moisture within the meat does not depend on its internal structure and this water moves in an unrestricted way. When there is sufficient free water in the product to replace that which is evaporating at its surface during drying, then the vaporization-evaporation process is at a maximum. As the product's moisture content falls during continuous moisture evaporation, its temperature gets close to the wet bulb temperature of the drying air (Fortes and Okos, 1980). This period during the drying process is identified as the constant rate drying period. Drying rate during this period is determined by factors consisting mostly of external parameters which include; temperature, relative humidity and velocity of the drying air (Fortes and Okos, 1980).

The dehydration process continues until at a point when there is not enough free moisture to maintain the maximum drying rate. This point is identified as the critical moisture content. The remaining moisture in the product is held within its cell structure and is known as bound moisture (Mujumdar and Menon, 1995). This means that the moisture cannot move freely through the product to its surface. This period of the drying process is known as the falling rate period (Mujumdar and Menon, 1995). During this period, there is a progressive decline in the rate of moisture transfer to the surface of the product and as a result, the drying rate falls (Perry, 2007). The drying rate at this point is mostly influenced by the internal parameters of meat, which are usually grouped together and expressed conveniently as a diffusion coefficient or a drying constant. According to Mujumdar and Menon (1995), for design and optimization purposes in drying, the drying constant is the most appropriate parameter. The most common form of algorithm used for drying rate calculation during the falling rate period is illustrated in Equation 1.1.

$$\frac{M - M_e}{M_0 - M_e} = e^{-kt} \tag{1.1}$$

where M represents the product's moisture content; M_e is the equilibrium moisture content; M_0 is initial moisture content; k is the drying constant and t is time.

The section of the equation on the left has a ratio which is normally referred to as the moisture content ratio (MR).

1.3.2. Energy in drying

Energy is the ability to do work and can be found in different forms, which include; heat, motion, electrical, light, nuclear energy, chemical and gravitational energy (Demirel, 2012). However, energy can be grouped into two main types; primary and secondary energy. Primary energy can be captured from the environment directly whereas secondary energy needs to be transformed from the primary type to another form such as fuel or electricity (Belyaev *et al.*, 2002). Primary energy can be divided further into three main groups: renewable energy (solar energy, biomass, hydroelectric energy, geothermal heat, ocean and wind energy) non-renewable energy/fossil fuels (natural gas, nuclear fuel, crude oil and coal) and waste (Demirel, 2012). Renewable energy can be naturally replenished as it originates from natural sources. In the developing world, the shortage of energy is still a major issue. On the other hand, drying is a very high energy consuming industrial process. To evaporate one litre of water, approximately 2.4 MJ of energy is required (Fuller, 2000). Even with availability of conventional energy sources like fossil fuels, concern over global warming focuses attention on energy intensive processes like drying, creating a need to reduce the amount of fossil fuels used and replacing them with renewable and non-polluting energy sources like solar energy (Fuller, 2000).

1.3.3. Sun drying

Sun drying of meat under direct influence of sun rays, natural temperatures, humidity and air circulation, is still a commonly used method of meat preservation in Sub Saharan Africa (Heinz, 1995). During the process of sun drying, heat from the solar radiation is transferred from the surrounding air (at ambient temperature) by convection, and then absorbed directly on the surface of the meat (Fuller, 2000). Part of the heat is conducted to the interior, causing temperature to increase within the meat and leading to a higher vapour pressure of the moisture in the meat compared to that of the surrounding air. Moisture, both liquid and vapour then move from the inside to the surface of the meat due to the resultant pressure and thermal gradients (FAO, 2007). The remaining energy is either used for moisture evaporation at the surface or lost by means of radiation and convection to ambient air.

Evaporation of water vapour to the surrounding air continuous until the air becomes saturated. However, the drying process continues if the air is replaced by less saturated air using natural convection or aided by wind energy (Bux, 2002). The drying process will continue to take place until the vapour pressure of moisture in the surrounding environment is same as that held within the product. At this point the moisture content of the meat is identified as the equilibrium moisture content (EMC). Where the rate of moisture absorption from the environment and desorption from the meat to the environment are in equilibrium. At ambient conditions and especially in environments where the relative humidity is high, the EMC is inadequately high for safe storing of the products (Ekechukwu and Norton, 1999). Other disadvantages of direct sun drying include; infection by micro-organisms, insect attack, contamination by dust and enzymatic reactions. This system is also time and labour intensive. The food products have to be sheltered at night, especially during bad weather and be protected from attack by domestic animals. Furthermore, since the temperatures attained during sun drying are low, the drying process takes longer. The slow drying allows for multiplication of micro-organisms in the initial period of moisture removal when the product's moisture content is still high, resulting in poor product quality (Fuller, 2000).

1.3.4. Solar drying

Solar drying: a more efficient system for solar energy utilization and can therefore, be considered as an elaboration of sun drying (Bala and Debnath, 2012). The objective of a solar dryer is to increase the moisture carrying capacity of drying air and ensure the product's EMC is sufficiently low (Ekechukwu and Norton, 1999). It does this by supplying the food with additional heat compared to that which is present at ambient temperature conditions. This decreases the relative humidity of the surrounding air and increases the vapour pressure of the moisture held within the product. Air gets into the dryer by means of natural or forced convection. As it passes through the collector, it receives more heat energy which is partly lost as it picks up moisture from the food in the dryer. For some types of solar dryers, the product's temperature may also be increased by absorption of solar radiation. Generally, more moisture can be held with warm air compared to cold air. The amount of moisture that can be held by the drying air within the dryer therefore depends on the amount held (absolute humidity) when it enters the dryer as well as the temperature to which it is heated in the collector (Buchinger and Weiss, 2001).

In summary, the advantages of solar drying in relation to open sun drying include: The higher temperature, lower humidity and increased air movement increases the drying rate, resulting in more complete drying for longer, giving a product with a longer shelf life (Fuller, 2000). The higher temperature also prevents insect infestation and the increased rate of drying minimizes the possibility of microbial growth and gives a higher throughput of food, hence a smaller drying area. There is increased protection from birds, insects, animals and dust as food is placed within an enclosed environment and the food products do not require to be relocated when it rains as the dryers are water proof (Buchinger and Weiss, 2001). The dryers can also be fabricated from low cost and locally available materials.

1.3.4.1. Solar drying systems

The need to serve the various purposes of drying products as per quality requirements, product characteristics and economic factors has led to the designing, development, and testing of a number of solar dryers (Fudholi *et al*., 2010). Solar dryers have been categorized into two major classes; natural convection and forced convection solar dryers (Bala and Debnath, 2012). The use natural convection solar dryers for dehydration of various agricultural products, has been reported in literature (Bala and woods, 1994; Oosthuizen, 1995; Sharma *et al*., 1995). Various designs exist including; indirect natural convection solar drier, cabinet type solar drier, and mixed mode AIT drier (Bala and Debnath, 2012). Numerous tests on the natural convection solar dryers, including studies on simulation and optimization of various products have been done in the tropical and subtropical regions (Bala and Woods, 1994; Simate, 2003).

In the natural convection type of solar dryers buoyancy establishes the airflow whereas in forced convection type, a fan (either operated by fossil fuel, electricity or solar module) provides the airflow (Bala and Debnath, 2012). One advantage of natural convection solar dryers is that a lower investment is required mainly due to low cost of design, maintenance as well as its simple operation compared to the forced convection type. However, the natural convection solar dryers have had limited success so far, mostly due to the insufficiently low drying rates (Oosthuizen, 1996) and difficulty in controlling the drying temperatures (Bala *et al.,* 2009). Researchers were therefore prompted to develop the forced convection type of dryers. These include; the solar assisted dryers, greenhouse type solar dryers, indirect forced convection solar dryers, roof integrated solar dryers and the solar tunnel dryers (Bala and Debnath, 2012).

1.3.4.1.1. Solar tunnel dryers

The development of the solar tunnel dryer took place in the early 1980s at the University of Hohenheim in Germany for dehydration of various agricultural commodities at a small scale level. The dryer has been tested widely and attained economic viability. The dryer comprises of a collector for heating the drying air, a drying chamber and fans (run by a solar module) for providing the air flow needed to create forced convection for efficient dehydration of the product.(Hossain and Bala, 2007) These are connected in series. A UV stabilized plastic sheet covers the collector and the drying unit which is secured like a sloping roof to prevent the entrance of water into the drying unit in case of rains (Bala *et al.*, 2009). The collector is painted black to act as an absorber (Bala *et al.,* 2009). The food to be dried is spread in thin layers and inserted into the tunnel dryer. The whole system is positioned horizontally on a raised platform (Figure1.1).

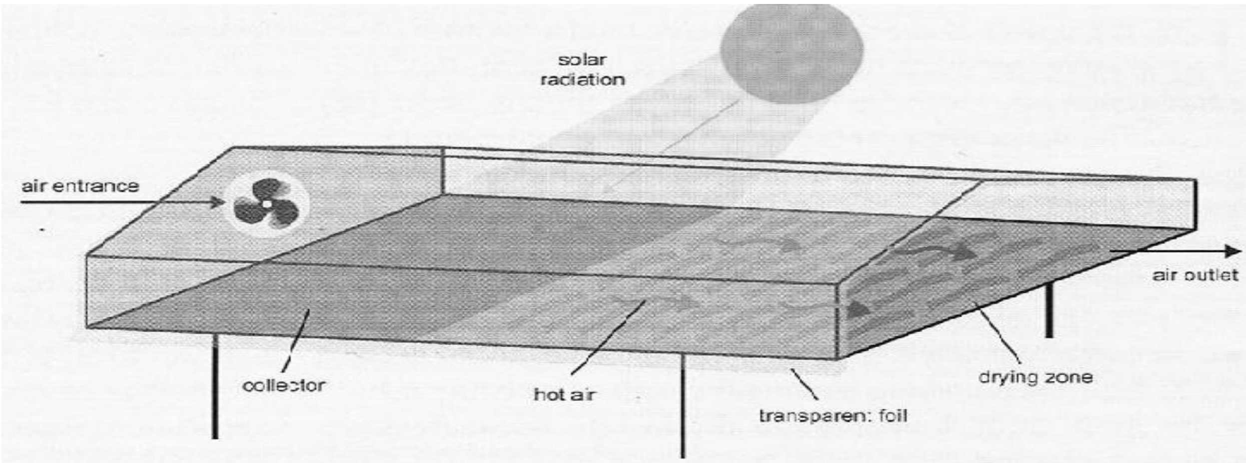

Figure 1.1: Solar tunnel dryer showing its mode of drying
(Hossain and Bala, 2007)

The main advantage of this type of dryer is that it is possible to regulate temperature during drying. During periods of high solar insolation, the collector receives more heat energy, which is meant to increase the temperature within the dryer but this is compensated by an increased air flow rate which regulates the drying temperature (Akarslan, 2012).

1.3.5. Drying modelling

Mathematical modelling of the drying system is the most applicable aspect of drying technology. Modelling is the use of a set of equations designed to describe the drying system as accurately as possible. In order to meet some specific drying requirements, design of the solar drying system should be taken into consideration. Simulation models are then developed for estimation of performance of a solar drying system as well as drying process optimization (Janjai and Bala, 2012). Drying kinetics, involving the heat and mass transfer processes of food materials involve complex operations and for some products, are scarce in the literature. Hence, experimental research and use of simplified models to represent the drying behaviour are required (Barrozo *et* *al*., 2001). However, is not economically feasible to do full-scale experimentation of most dehydration processes for different products. Therefore simulation models are sometimes employed in drying kinetics studies (Steinfeld and Segal, 1986).

1.3.6. Sorption isotherms

Food sorption isotherms describe the thermodynamic relationship between water activity and the equilibrium moisture content of foods with temperature and pressure kept constant. The sorption curves define the state of hygroscopic equilibrium of various products (Lemus *et al*., 2011). To understand the engineering operations related to dehydration (Maskan *et al*., 1998) and to ensure proper design and efficient optimization of drying equipment, good knowledge and understanding of sorption isotherms is key (Lemus *et al*., 2011). Moisture sorption isotherms can also be used for prediction of potential changes in food stability and packaging material selection (Basu *et al*., 2006). They are therefore very valuable tools for researchers in food science and technology.

Sorption isotherms can either be generated from desorption or an adsorption process. The sorption isotherms of food products can be measured using different techniques. These include: gravimetric, hygrometric or manometric techniques (Iglesias and Chirife, 1978). The gravimetric method involves measuring the weight of the sample with a balance whereas the hygrometric and manometric methods measure the relative humidity of air and vapour pressure of water respectively when at equilibrium with a sample at given moisture content (Iglesias and Chirife, 1978). Several mathematical models have been developed with the aim of determining moisture sorption isotherms of various products. These include; nonlinear, linear and regression models.

In most cases, some of these models are product specific and sometimes only give appropriate predictive ability at certain water activity ranges (Lemus *et al*., 2011).

The models that are most commonly applied for moisture sorption description of food products include the BET, Oswin ,GAB, Halsey, Iglesias-Chirife, Henderson, Peleg and Smith models (Sahin and Gülüm, 2006). Generally, experimental determination rather than theoretical estimation of sorption isotherms for meat is important. This is mainly due to the complex composition of meat products and the effects of drying and storage parameters on meat structure (Adam *et al*., 2000). Some review papers on sorption isotherms of different meat products are available in literature. Various models for mathematical description of the sorption isotherms are also available (Kaymak-Ertekin and Gedik, 2004; Seid and Hensel, 2012; Mousa *et al.*, 2014). Studies on modelling of meat sorption isotherms at different temperatures have also been done (Clemente *et al*., 2002). However modelling of meat sorption isotherms at the specific temperatures encountered during the drying process is necessary.

1.3.7. Drying kinetics equations

For a good description of drying kinetics of food products, it is required to establish an appropriate mathematical model and find numerical values for the model parameters (Efremov, 2013). The most appropriate tool for characterizing the drying parameters of most food products is by use of the thin layer drying procedure (Akgun and Doymaz, 2005; Aknipar *et al*., 2003). Currently, the categories of thin layer drying models that are used for describing the drying characteristics of agricultural products include; empirical, theoretical and semi-theoretical models (Demirats *et al*., 1998; Midilli *et al*., 2002). In literature, drying of a number of food products has been described mostly by using semi-theoretical models: By non-linear regression on experimental data and using equations in exponential form (Kemp *et al*., 2001; Mujumdar, 2007). Several equations have been used in different studies for modelling the drying behavior of different products including meat (Kemp *et al*., 2001; Efremov 2002; Mujumdar, 2007).

1.3.8. Quality changes in meat during drying

Drying causes many changes to the various quality properties of meat and meat products (FAO, 1995). The properties of dried meat products can be classified into two broad categories: the engineering properties of the drying products and properties, which are related to product quality. The engineering properties of dried food systems are important for designing of food processes and the processing equipment and for efficient operation and control of drying processes. These include; effective moisture diffusivity, effective thermal conductivity, specific heat, equilibrium moisture content, and viscosity (Krokida and Maroulis, 1999). On the other hand, the quality related properties of dried meat products can be divided into a number of groups. These include; optical properties (appearance, color), structural properties (porosity, density, specific volume, pore size), textural properties (tensile test, compression test), sensory properties (aroma, flavor, taste), thermal properties (denatured), rehydration properties (rehydration capacity, rehydration rate) and nutritional properties (vitamins, proteins) (Krokida and Maroulis, 1999).

Undesirable changes to meat due to dehydration are caused by different chemical or biochemical reactions such as fat oxidation, oxidation of pigments, browning reactions, and losses of nutrients and physical changes such as shrinkage. These result in various changes in colour, texture or odour of the dried meat products (Mujumdar and Devahastin, 2000). High temperature drying also causes the case hardening effect giving an improperly dried product (Mishra *et al.*, 2017).

Most of the changes in meat during drying are as a result of denaturation of meat proteins. Protein denaturation reduces the water holding capacity and results in shrinkage of muscle fibers, leading to a harder and more compact tissue texture. The denaturation of heme proteins as well as oxidation of myoglobin pigments result in darkening of the products (Haard, 1992). Different drying techniques have also significant effects on the rehydration capacity of dehydrated meat products. Rehydration depends on the water absorption capacity, water holding capacity of muscle fibres and the formation of spaces within muscle fibres, affecting dehydration, rehydration and textural quality of meat (Laopoolkit and Suwannaporn, 2011). Drying techniques also play a major role in development of porosity in the meat samples. A higher porosity in meat structure leads to a higher rehydration ratio of the dried meat product (Rahman *et al.*, 2005).

1.3.9. Quality of dehydrated meat during storage

Microbial spoilage and lipid oxidation (leading to rancidity), are the most important deterioration processes in meat during storage. Lipid oxidation may change the colour, aroma, flavor, texture and even the nutritive value of the product (Fernandez *et al.*, 1997). Many pathogenic bacteria like *Salmonella*, *Staphylococcus aureus*, *Clostridia* etc. originating from raw meat may survive the drying processes and lead to deterioration during storage. However, the main spoilage organisms associated with dried meat and meat products are moulds, which require a low a_w for growth (Mishra *et al.*, 2017). The type and extent of spoilage in dried foods during storage is determined by several factors. These include; moisture content, temperature, exposure to light, oxygen concentration and duration of storage. The storage stability of some products can be extended by storage in an inert atmosphere or elimination of oxygen during packaging (Singh *et al.,* 2009). Presence of light in some foods can also initiate or accelerate some deteriorative reactions in dried foods such as; destruction of nutrients such as thiamine and oxidative rancidity of lipids (Brown and Williams, 2003).

However, the most important factor that determines stability of dehydrated foods is the product's moisture content. For long-term storage of most dehydrated foods, their optimal moisture content corresponds to the B.E.T. monolayer value (Mujumdar, 2014). However water activity (a_w) is more important in foods stability studies compared to the moisture content of products. Lipid oxidation is also influenced by water activity of stored foods and is highest at very high and very low water activities. This is due to the increased movement of pro-oxidants in the former and presence of more oxygen in the latter case (Weiss *et al.,* 2010). Generally, there is an inverse relationship between the storage stability of dehydrated foods and storage temperature. The rate at which a deleterious reaction takes place as well as the kind of spoilage mechanism prevailing in the food is determined by the storage temperature. Some of these reactions include; enzyme reactions, hydrolysis, lipid oxidation, non-enzymic browning and protein denaturation. Activation energies for these reactions differ and may depend on the amount of moisture present in the product (Brown and Williams, 2003).

Dehydrated foods therefore need to be provided with adequate packaging in order to be protected from these deteriorative reactions. Different packaging methods, packaging materials and days of storage also significantly affect the sensory properties of the dried products (Mishra *et al.,* 2012). The three sensory parameters which are mostly used by consumers to readily judge meat quality are appearance, flavour and texture (Liu *et al.*, 1995). Visual appearance is the most important of these as it strongly influences the consumer's decision to purchase or not (Faustman and Cassens, 1990).

1.4. PROBLEM STATEMENT

Beef represents about 73% per cent of the total meat consumed in Kenya (FAOSTAT, 2016), mostly produced under the pastoral production system in the arid and semi-arid lands. Because of the lack of cold storage facilities and climatic conditions in these areas, it is practically not possible to keep meat and meat products fresh for any length of time. Due to its rich nutrient matrix and high water activity, meat is highly perishable and can undergo deterioration from time to time. This can result to post-harvest losses which can be as high as 50 per cent of the meat produced, leading to food insecurity and reduced profit margins to value chain actors in Kenya (Lewa, 2010). In the absence of a cold chain, drying of meat is still the most practical way to preserve and store meat in the developing nations with warm climate (FAO, 2001). This can create an avenue to maintain meat safety and quality thus reducing post-harvest losses. Currently, there are many traditional dried meat products that exist in Sub-Saharan Africa. However, non-controlled processes and lack of appropriate equipment cause wide variations in their stability and quality. This creates a need for upgrading of the processing and preservation operations within the region with an aim of improving the quality of the meat drying processes.

1.5. JUSTIFICATION OF THE STUDY

Quality of the drying process is a function of drying time, product quality as well as energy consumption and in order to optimize the process, all the three aspects need to be accounted for.

In terms of energy consumption, thermal drying competes with distillation for being a highly energy intensive unit operation of food processing. This is mainly as a result of the high latent heat of vaporization of water which is usually removed from food products during dehydration (Jangam *et al*., 2011). What makes the situation more challenging is the rising energy cost, in spite of the fact that the source of heat for most of the dryers used in meat processing is either direct electric energy or fossil fuel. This has forced the users of these dryers to go for other energy options which are more cost effective (Muhlbauer, 1986). On the other hand, shortage of energy particularly in the developing countries is still a major issue and even where there is plenty of conventional energy, there is still pressure to minimize on use of fossil fuels. This is due to issues like emission of hazardous gases and carbon foot print which have recently received a lot of attention due to the issue of global warming (Fuller, 2000). Development of new and renewable energy resources should therefore be given more attention, so that the cost of energy and the impact of conventional sources of energy on the environment are reduced. Solar energy can serve as a sustainable source of energy as it is both renewable and environment friendly (Xie *et al*., 2011).

Sun drying has been practiced for many years particularly in the tropics and subtropics where there is abundance of solar radiation, to preserve various agricultural products for local consumption, (Bala *et al.*, 2009). However, for large-scale production open sun drying becomes a challenge because of several limitations. These include; large area requirement, high labour costs, insect infestation, possible degradation due to microbiological or biochemical reactions, inability to control the drying process and so on. Additionally, long drying times (sometimes up to a month or more) can result to post-harvest losses due to spoilage. As a result, the sun dried products are usually of poor quality and do not match the international standards (Visavale, 2012). Therefore the introduction of suitable drying technologies for meat is critical in relation to product quality improvement and post-slaughter loss reduction. Solar tunnel drying of agricultural products is therefore an attractive way of utilizing solar energy as well as post-harvest loss reduction and dried product quality improvement compared to open sun-drying (Mühlbauer 1986). Modelling of the solar tunnel drying system as well as product quality evaluation are thus important tools for characterizing the drying system; so that drying process control and optimization is possible (Janjai and Bala, 2012). The modelling and simulation processes of beef will help in better understanding the products' behavior during drying for better management of the solar drying process in the pastoral regions of Kenya, leading to reduction of meat losses in its value chain.

1.6. STUDY OBJECTIVES

1.6.1. Main objective

The objective of this study was to model the drying kinetics and determine the quality parameters of solar dried beef.

1.6.2. Specific objectives

The specific objectives of this study were:

1. To determine desorption isotherms for beef

2. To determine drying characteristics of beef in a laboratory simulated dryer
3. To model the drying kinetics of beef in a solar tunnel dryer
4. To determine beef quality changes during drying and storage

1.7. RESEARCH QUESTIONS

1. What are the equilibrium moisture content values, at particular relative humidities of the environment, during desorption of moisture from beef at specific temperatures?
2. To what extent does drying air temperature and sample thickness affect the drying kinetics of beef under controlled atmospheric conditions?
3. What are the effects of drying air temperature and slice thickness on the physical and microbial quality characteristics of dried beef?
4. To what extent does drying under varying atmospheric conditions affect the drying kinetics of beef?
5. Does solar tunnel drying, packaging type and storage time affect the physico-chemical and microbial properties of dried beef?

1.8. THESIS LAYOUT

This thesis is divided into eight chapters. **Chapter one** gives the general introduction. It introduces the research and brings out the key concepts used in the study. **Chapter two** brings out the effects of temperature on the desorption isotherms of beef. **Chapter three** elaborates on the effects of drying air temperature and slice thickness on the drying kinetics of beef. **Chapter four** brings out the effects of drying air temperature and sample thickness on the physical and microbiological properties of dried beef. **Chapter five** elaborates on the effect of sun and solar drying on the drying kinetics of beef. **Chapter six** brings out the physico-chemical and microbial quality characteristics of beef dried in a solar tunnel dryer and stored under different conditions. **Chapter seven** summarizes the general conclusions and gives the recommendations of the study

CHAPTER 2: EVALUATION OF DESORPTION ISOTHERMS FOR BEEF

ABSTRACT

Food sorption isotherms describe the thermodynamic relationship between water activity and the equilibrium moisture content of foods with temperature and pressure kept constant. The aim of the present study was to evaluate the effect of temperature on the desorption isotherms of beef at 30-60 °C. The standard static gravimetric technique was used in determining the desorption isotherms at values of water activity between 0.05 and 0.9. Effect of water activity and temperature on the equilibrium moisture content was then evaluated. Fitting of experimental sorption data was done using the GAB, BET and Oswin models and fitting quality determined by use of the coefficient of determination (R^2) as well as the standard error of estimate (SEE). The net isosteric heat of sorption was then established for samples with various levels of moisture content. The equilibrium moisture content (EMC) decreased with increasing temperature at constant water activity, while EMC increased with increasing water activity at constant temperature. Therefore, the critical moisture content, which was considered as the stable moisture content for safe drying of beef (at water activity value of 0.6) was lower at 60 °C (0.10 kg moisture/kg dry matter) and higher at 30 °C (0.22 kg moisture/kg dry matter). The net isosteric heat of sorption decreased with increasing moisture content. The GAB and Oswin models had the best fit for the desorption data. The desorption isotherms and the isosteric heat of sorption can therefore help in understanding the interactions between solids and water at different stages during beef drying at the experimental temperature conditions.

2.1. INTRODUCTION

Moisture sorption isotherms describe the relationship between the equilibrium moisture content (EMC) and water activity of foods at constant pressure and temperature. Equilibrium moisture content is a thermodynamic entity with practical relevance in both drying and storage of foods (Shivhare *et al*., 2004). Its definition is given as; the moisture content when vapour pressure of water present in the surrounding environment is in equilibrium with that in a food material (Shivhare *et al*., 2004). Water activity can be defined as the ratio of vapour pressure of water present in food to the vapour pressure of pure water at the same temperature as given in Equation 2.1.

$$a_w = \left(\frac{p}{p_o}\right)_T = \frac{ERH}{100} \qquad (2.1)$$

where a_w is water activity; p is vapour pressure of water present in food; p_o is vapour pressure of pure water; ERH is the equilibrium relative humidity (%) and T is absolute temperature (K).

Water in food affects its nature and physical properties in a complex manner as a result of its interactions with different particles (dispersed particles, solutes and colloids) (Park *et al*., 2001). The way in which moisture is bound in a food material is depicted by the shape of the isotherm. Stronger water molecule interactions give a lower water activity and the food product becomes more stable. Control of water activity is one of the main concerns during food preservation processes as it reflects the water that is available for microbiological growth and deteriorative reactions (Al Muhtaseb *et al.*, 2002).

Information gathered on moisture sorption isotherms of various food products can be useful for; modelling moisture changes occurring during drying, quality predictions, assessing packaging problems, calculating shelf life of products and ingredient mixing predictions (Lemus *et al.*, 2011). They can also be used for designing and optimization of drying equipment and other engineering purposes related to dehydration (Maskan and Göğüş, 1998). As much as there are a number of mathematical models that have been used to for describing several food moisture sorption isotherms, there is no single model that gives accurate results for all types of foods and for the whole water activity range (Lemus *et al.*, 2011). The most common equations that have been used in literature are the, the BET, Langmuir and Iglesias-Chirife equations together with the Smith, Halsey, GAB, Oswin, Peleg and Henderson models (Sahin and Gülüm, 2006).

During sorption isotherm determination, one essential parameter that must be known is the heat of sorption. The difference between the total heat of sorption of water (Q_{st}) in a material and the heat of vaporization is known as the net isosteric heat of sorption (q_{st}). It is the amount of energy greater than the heat of vaporization of water and associated with the sorption process (Rizvi, 1995; McLaughlin and Magee, 1998). During desorption it represents the energy that breaks the intermolecular forces between the water molecules and the surface of the adsorbent and it symbolizes the energy released during adsorption (Rizvi 1995). The energy required during dehydration processes can therefore be estimated from the net isosteric heat of sorption. At a given moisture content during dehydration of a given food, when the net isosteric heat of sorption starts to approach the latent heat of vaporization, the amount of 'bound water' present can also be closely estimated (McLaughlin and Magee 1998).

Some studies on sorption isotherms of different food materials are available in literature (Kaymak-Ertekin and Gedik, 2004; Seid and Hensel, 2012; Mousa *et al.*, 2014). However, information on desorption isotherms of beef is scanty. Among the factors that influence the shape and characteristics of moisture sorption isotherms, temperature is the most important (Martinez Las Heras *et al.*, 2014). Temperatures found during the solar drying process in the arid and semi-arid areas of Kenya vary from around 30 to 60 °C. There is therefore a need to evaluate the moisture sorption behavior of beef at these solar drying temperatures so that the characteristics of the product during drying are better understood. The present study was therefore aimed at experimentally evaluating the desorption isotherms of beef at 30-60 °C.

2.2. MATERIALS AND METHODS

2.2.1. Sample collection and preparation

Meat (beef) of good microbial quality from the round of the hind quarter of an inspected male carcass was purchased from a local slaughter house in Nairobi, Kenya. Trimming of excess fat was done to prevent rancidity during the experiment. It was then cleaned and stored in a cold room for 48 h at 5 °C prior to the start of experiments so that the storage conditions would be kept the same for all samples. The meat was cooled overnight at 0 °C to obtain enough consistency for cutting and cut into thin strips of 5 cm long, 5 cm wide and 1 cm thick (weighing approximately 25g), along the direction of its fibers. Initial moisture content of beef was determined in triplicates using a drying oven fixed at temperature of 105 °C (AOAC, 2005; method 967.08) and the average values reported as 3.29 kg water/kg dry matter.

2.2.2. Experimental design

The standard static gravimetric technique was applied in determining the desorption isotherms of fresh beef whereby saturated salt solutions were used to maintain constant relative humidity according to the COST 90 method (Wolf *et al.,* 1985). The salts had water activity values ranging from 0.05 to 0.9 as shown in Table 2.1

Table 2.1: Water activities of the saturated salt solutions used in the desorption experiments

	Water activity			
Salt	30 °C	40 °C	50 °C	60 °C
KOH	0.0738	0.0626	0.0572	0.0549
LiCl	0.1182	0.1125	0.1110	0.1073
CH_3COOK	0.2160	0.2012	0.1890	0.1600
$Mg(Cl)_2.6H_2O$	0.3238	0.3159	0.3159	0.2926
K_2CO_3	0.4317	0.4320	0.4322	0.4327
NaBr	0.5602	0.5320	0.5320	0.4970
$NaNO_3$	0.7312	0.7100	0.7100	0.6735
NaCl	0.7569	0.7540	0.7444	0.7430
KCl	0.8362	0.8232	0.8120	0.8030
KNO_3	0.9188	0.8835	0.8521	0.8478

(Greenspan, 1977)

Ten glass desiccators each with an insulated lid containing different saturated salt solutions were placed for 24 h in a hot air oven set to fixed temperatures for the salt solutions to equilibrate. Triplicate meat samples were placed on the perforated base approximately 5 cm above the surface of the desiccators. In order to prevent fungal activity, a small amount of toluene was placed in each hygrostat (Wolf *et al*., 1985). Weights of beef samples were recorded after every 4 days and this was done until the sample weights were constant. The AOAC (2005) method 967.08 was used in equilibrium moisture content (X_{eq}) determination for each sample as given in Equation 2.2.

$$X_{eq} = \frac{M_w - M_d}{M_d} \tag{2.2}$$

where X_{eq} is the equilibrium moisture content (kg water/kg dry matter); M_w and M_d are the sample masses before and after drying respectively.

Each set of experiment was repeated three times and mean value of equilibrium moisture content recorded.

2.2.3. Analysis of sorption data

Fitting of the experimental sorption data was done using three models; the GAB, BET and Oswin models (Table 2.2).

Table 2.2: Moisture sorption isotherm models

Model	Equation	References
GAB	$X_{eq} = \frac{X_M C K a_w}{(1 - K a_w)(1 - K a_w + C K a_w)}$	(Van Den Berg, 1985)
BET	$X_{eq} = \frac{X_M C a_w}{(1 - a_w)(1 + (C - 1) a_w)}$	(Brunauer *et al*., 1938)
Oswin	$X_{eq} = a \left(\frac{a_w}{1 - a_w}\right) \hat{} b$	(Oswin, 1946)

where a_w is the water activity; C, K, a and b are constants; X_{eq} and X_M are the equilibrium moisture content and monolayer moisture respectively (kg water/kg dry matter).

Model coefficients were estimated by nonlinear regression analysis of the experimental sorption data using Minitab (Version 18.0, Minitab Inc., USA) software package. The goodness of fit of the models was assessed using the coefficient of determination (R^2) (Equation 2.6) calculated numerically using Excel and the standard error of the regression (standard error of estimate) (Equation 2.7) generated by Minitab. Low values of SEE and high values of R^2 were considered for evaluating goodness of fit of the curve to the equation.

$$R^2 = \frac{\sum_{i=1}^{N} (M_{p,i} - M_{e,avg})^2}{\sum_{i=1}^{N} (M_{e,i} - M_{e,avg})^2}) \tag{2.6}$$

$$\mathrm{SEE} = \sqrt{\frac{\sum_{i=1}^{N} (M_{e,i} - M_{p,i})^2}{N}} \tag{2.7}$$

where M_p is the predicted EMC value; M_e is the experimental EMC value and N is the number of experimental data.

2.2.4. Net isosteric heat of sorption determination

The Clausius–Clapeyron equation was used for the determination of the net isosteric heat of sorption (q_{st}) of water in beef as expressed in Equation 2.8, with the assumption that the q_{st} value does not differ significantly with temperature.

$$a_w = a_0 exp\left(\frac{-q_{st}}{RT}\right) \tag{2.8}$$

where a_w is water activity at constant EMC; a_o is a constant; R is the universal gas constant (kJ/mol.K) and q_{st} is the net isosteric heat of sorption (kJ/mol).

GAB model was used to obtain the water activity values at constant moisture content for each experimental temperature. For selected moisture contents, the net isosteric heat of sorption was assessed by plotting ln(a_w) vs (1/T) and computing q_{st} from the slope which was represented by q_{st}/R. Effect of moisture content on q_{st} values for beef was then determined.

2.3. RESULTS AND DISCUSSION

2.3.1 Effect of water activity and temperature on equilibrium moisture content of beef

The values obtained for EMC for beef at different temperatures and water activities are shown in Figure 2.1. The mean equilibrium moisture content values ranged from 0.04 to 0.59, 0.03 to 0.42, 0.03 to 0.36 and 0.11 to 0.24 (kg water/kg dry matter) at temperatures of 30 °C, 40 °C, 50 °C and 60 °C respectively, within the range of relative humidity of 5%-90%. The desorption isotherms for beef were sigmoid-shaped curves and therefore belonged to the Type II isotherms of the Brunauer *et al*. (1938) classifications, common for most food products (Al-Muhtaseb *et al.*, 2002).

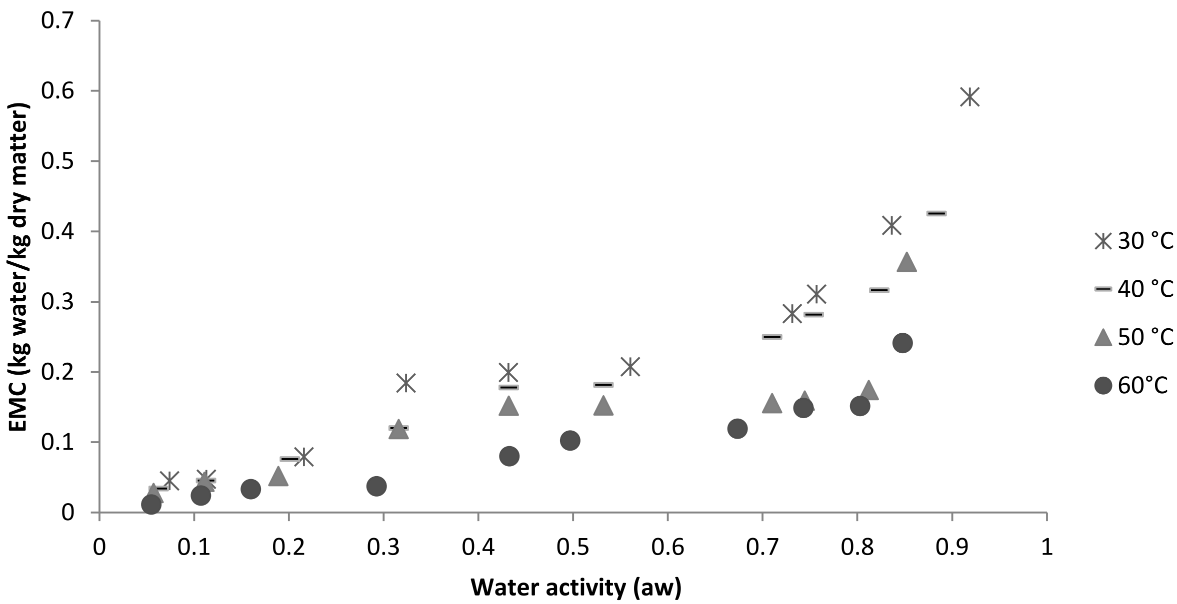

Figure 2. 1: Desorption curves of fresh beef

There was an increase in EMC of beef with increase in a_w at different temperatures (Figure 2.1) whereas increasing temperature at all levels of water activity decreased EMC values. Mobility of water molecules within a food system and the dynamic equilibrium between vapour and the adsorbed phases is affected by temperature. Singh *et al*. (2001) reported that at constant water activity, increasing temperature decreases the amount of adsorbed water. Palipane and Driscoll (1992) suggested that at higher temperatures activation of water molecules to higher energy levels occurs, allowing them to break away from their sorption sites which decreases their EMC values, whereas Iglesias and Chirife (1982), noted that at higher temperatures, food became less hygroscopic. The critical moisture content for beef (at water activity value of 0.6) was found to be 0.10 and 0.22 (kg moisture/kg dry matter) at 60 and 30 °C respectively (Figure 2.1). Microbial growth generally does not occur below the water activity of 0.6, meaning that the EMC values found at this water activity within the experimental temperature range can be considered as the stable moisture content for safe beef drying.

2.3.2. Modelling of sorption isotherms

The effectiveness of the sorption models for describing the desorption isotherms for beef at the experimental temperature range was tested and the coefficient of determination (R^2) and standard error of estimate (SEE) values for each model reported in Table 2.3. The lowest values and highest values of SEE and R^2 respectively were found for the GAB and Oswin models. Consequently, they were considered the best models for representing the desorption isotherms of beef within the temperature experimental range of 30-60 °C, and water activities of between 0.05 and 0.9 (Table 2.3).

Table 2.3: Statistical parameters and model constants for GAB, BET and Oswin models

		Statistical parameters		Model constants				
Model	Temp. (° C)	R^2	SEE	X_M	C	K	a	b
GAB	30	0.9759	0.0302	0.1175	11.1308	0.8785		
	40	0.9851	0.0177	0.1144	7.6441	0.8209		
	50	0.7823	0.0499	0.0617	29.1549	0.9279		
	60	0.9473	0.0180	0.0484	8.34602	0.9930		
BET	30	0.8919	0.0815	0.0577	5.64802E+17			
	40	0.8991	0.0518	0.0572	221.0820			
	50	0.7872	0.0481	0.0473	141.9250			
	60	0.9421	0.0189	0.0366	19.1733			
Oswin	30	0.9795	0.0262				0.1897	0.4660
	40	0.9857	0.0164				0.1658	0.4586
	50	0.7805	0.0466				0.1249	0.4517
	60	0.9532	0.0167				0.0820	0.5719

where R^2 and SEE are coefficient of determination and standard error of estimate respectively; C, K, a and b are constants and X_M is monolayer moisture (kg water/kg dry matter).

Boquet *et al*. (1978) considered the Oswin equation to be the best one for representing the isotherms of starchy foods, and reasonably good for meat and vegetables. Lomauro *et al.* (1985) stated that for over 75% of the food isotherms (fruits, vegetables, starchy foods and meat products) the GAB model gave a good fit. Considering the fact that the GAB model parameters have a physical meaning and can be explained theoretically, it therefore appears to be more suitable for describing moisture sorption of foods (Seid and Hensel, 2012). Monolayer moisture content (X_M) for the GAB model decreased as the experimental temperature increased (Table 2.3). Similar results were reported by Singh *et al*. (2001; 2006). The X_M values of the beef samples in this work ranged between 0.0484 and 0.1144 kg water/kg dry mass. The monolayer moisture content represents a value that has to be attained so that the physical and chemical stability of dehydrated foods is assured for it indicates the water that is strongly adsorbed to specific sites at the food. Rates of deteriorative reactions at or below this value are usually minimal (Choudhurya, *et al.,* 2011). The availability of hydrophilic sites and ability of polymers to form hydrogen bounding is diminished at higher temperatures thus the amount of monolayer moisture is reduced (Quirijns *et al*., 2005). Moreover, when the temperature of a product is increased, water molecules gain greater kinetic energy, which enables them to get away from their binding positions (Erbas *et al*., 2005).

The constants C and K give indications of energies of interaction between food and water molecules. The energy constant representing multilayer water (K) for the GAB model was highest at 60 °C. Multilayer water is water present in association with neighboring molecules by water-solid substrate or water-water hydrogen bonding. A high K value indicates that water is strongly bound (Timmerman *et al*., 2001).

Figures 2.2, 2.3 and 2.4 show the experimental and predicted points of desorption isotherms at 40 °C by GAB, BET and Oswin models respectively. The GAB and Oswin model values had visually good fits to the experimental sorption isotherm values compared to the BET model.

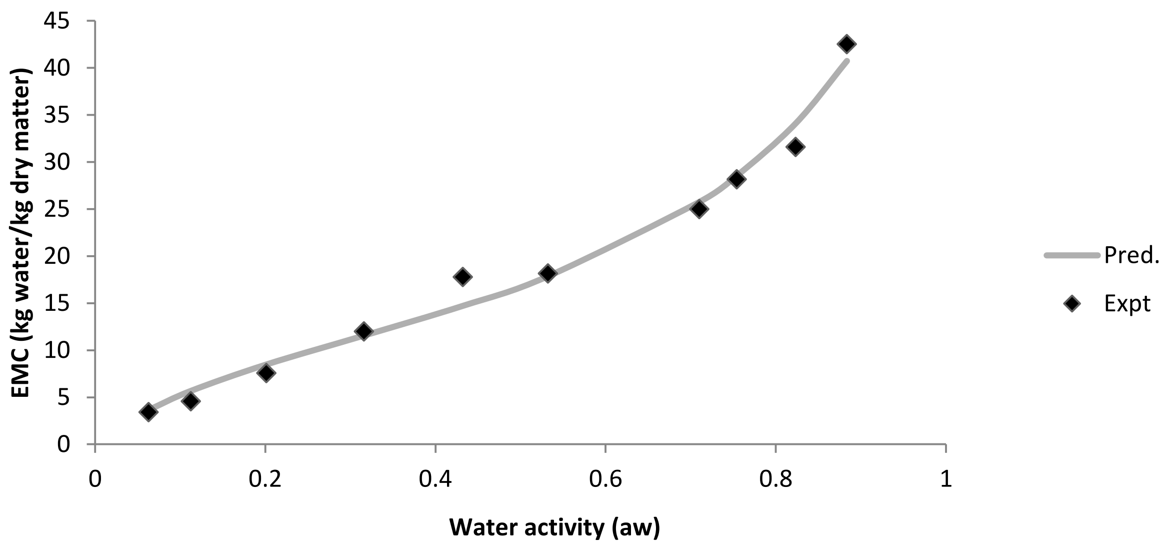

Figure 2.2: Predicted and experimental desorption curves of beef using GAB model at 40 °C.

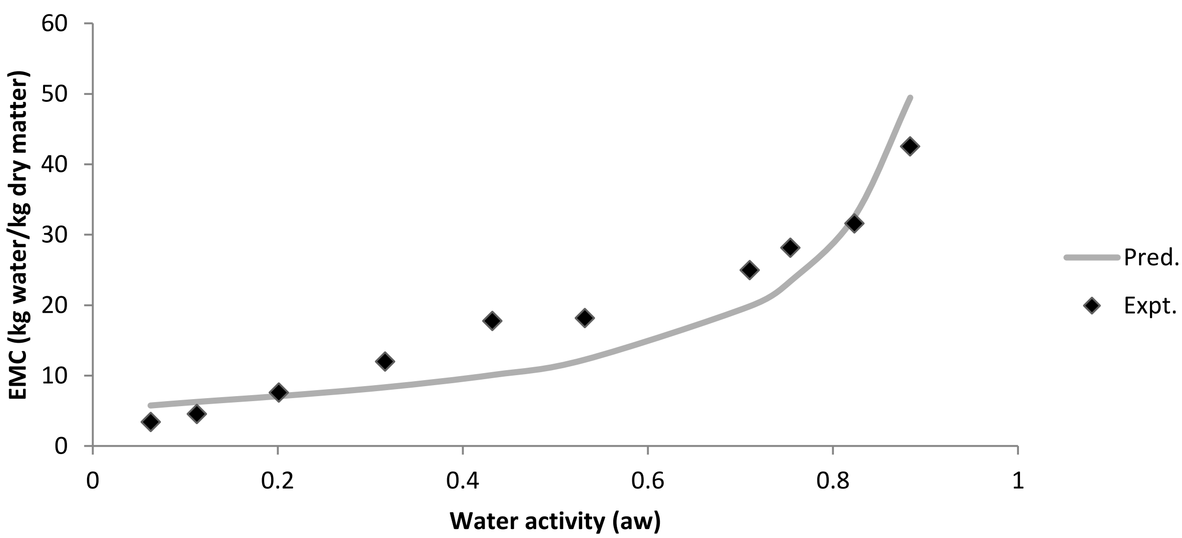

Figure 2.3: Predicted and experimental desorption curves of beef using BET model at 40 °C.

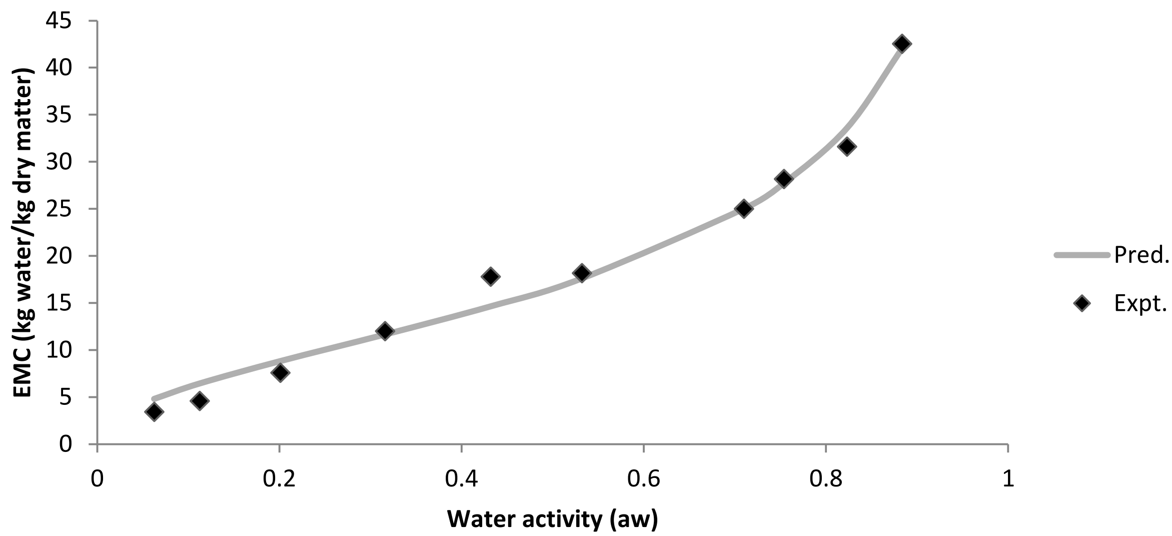

Figure 2.4: Predicted and experimental desorption curves using Oswin model at 40 °C.

2.3.3. Net isosteric heat of sorption (q_{st})

Figure 2.5 shows a plot of natural logarithm of water activity (ln (aw)) vs reciprocal of absolute temperature (1/T) for specific values of EMC (kg water/kg dry matter) of fresh beef. Specific water activity values were assessed using the GAB equation for each case.

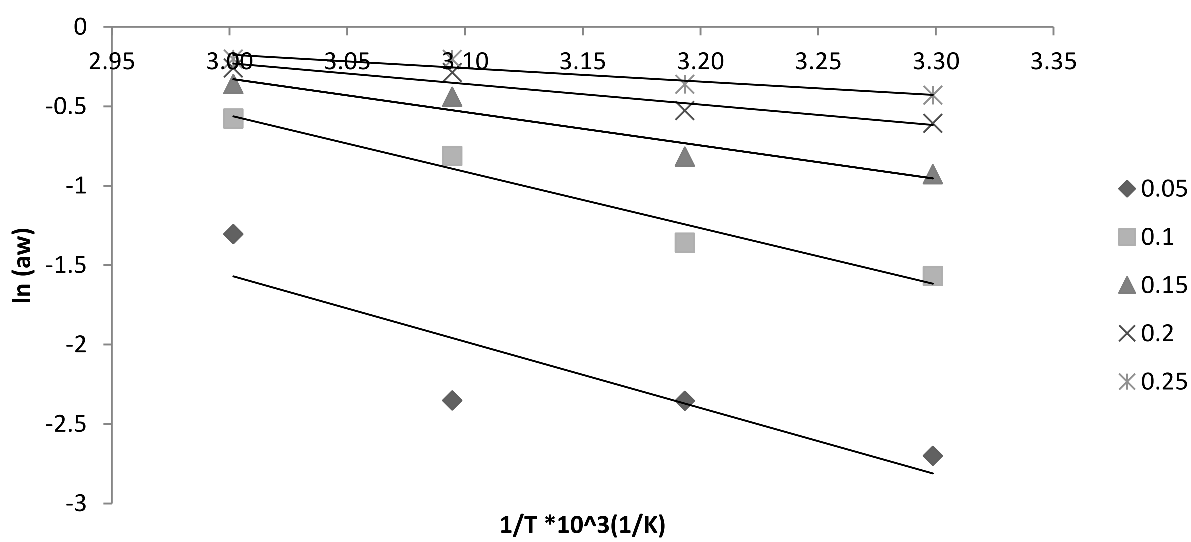

Figure 2.5: Graph of ln (a_w) vs. 1/T for heat of sorption calculation at different moisture levels.

From the graph, it was obvious that q_{st} was independent of temperature and it was also observed that an increase in EMC decreased the slopes of the curves leading to a decreased net isosteric heat of sorption. Similar behavior for other foodstuffs has been reported by other researchers (Mittal and Usborne, 1985; Tsami *et al.*, 1990).

In Figure 2.6, a plot of the net isosteric heat of sorption as a function of equilibrium moisture content is shown. The q_{st} was taken from the slopes of Figure 2.5 multiplied by the universal gas constant (R). There was a decreased in q_{st} with increase in moisture content (Figure 2.6).

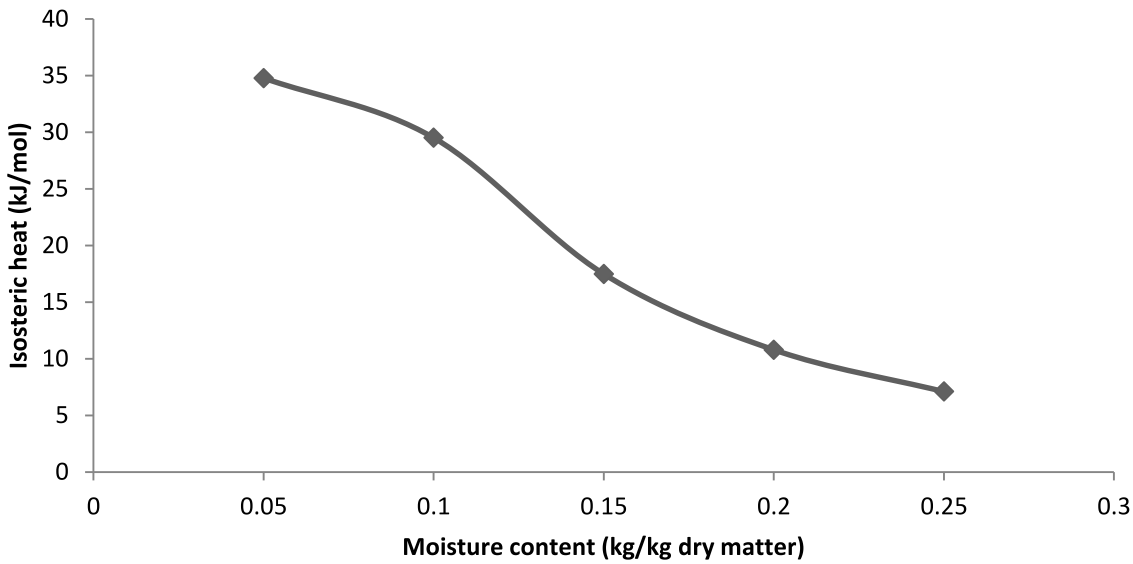

Figure 2.6: Variation between net isosteric heat of sorption and moisture content of beef

With the continuous decrease in moisture content during desorption, it gets to a point where only the monolayer moisture is left. The water molecules become tightly bound with high interaction energies to the surface of the product and to the sorption sites, resulting in increased q_{st} values. The heat of desorption approaches zero as moisture content increases, indicating that total heat of sorption approaches the heat of vaporization of free water. Water molecules act like they are in the liquid state at this stage. Therefore, less energy is needed for drying a material when the moisture content is still high (during the initial stages of drying).

2.4. CONCLUSIONS

Desorption isotherms for beef are sigmoid-shaped curves, Type II isotherms. At any given temperature, the equilibrium moisture content (EMC) of beef increases with increase in water activity and decreases with increase in temperature at any level of water activity. The GAB and Oswin models have the best fit for the sorption isotherm data and the net isosteric heat of sorption for beef increases with decrease in moisture content.

CHAPTER 3: INFLUENCE OF DRYING AIR TEMPERATURE AND SLICE THICKNESS ON THE DRYING KINETICS OF BEEF

ABSTRACT

One of the important areas of drying technology is modelling and simulation of the drying processes. The objective of this study was to determine the influence of drying air temperature (30-60 °C) and slice thickness (2.5-10 mm) on the convective thin-layer drying kinetics of beef. Drying was done in a cabinet dryer. The experimental data were fit to five semi-theoretical models, with the aim of predicting drying characteristics of beef and evaluation of the fitting quality of models done using standard error of estimate (SEE) and the coefficient of determination (R^2). Effective moisture diffusivity (D_{eff}) was then established from the drying data. Drying time and drying rates increased with an increasing temperature but decreased with increased slice thickness. However, there was overlapping of drying curves at 40-50°C. Among the selected models, Page model gave the best prediction of beef drying characteristics. Effective moisture diffusivity (D_{eff}) ranged between 4.2337 x 10^{-11} and 5.5899 x 10^{-10} m^2/s, increasing with an increasing air temperature and beef slice thickness. The diffusion model used in this study was more applicable for thinner slabs dried at a higher temperature. Therefore, for optimization of drying of beef samples in terms of time and effective application of the diffusion model, a higher temperature and thinner beef slices would be recommended.

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3.1. INTRODUCTION

Drying is a unit operation whereby heat and mass transfer processes occur simultaneously. Heat penetrates into the product and causes transfer of moisture from inside of the food product to its surface with subsequent evaporation to the air stream as vapour (Tulek, 2011). The reasons for drying different types of food products are extremely diverse: from reducing bulk during transportation to increasing the shelf-life of agricultural commodities. As one of the most extensively used methods for preservation of food, drying prevents the deterioration of perishable products and ensures their availability during periods of scarcity.

Some important areas in drying technology include modelling of the drying process as well as the drying equipment (Akpinar *et al.,* 2006). Drying simulation for many agricultural commodities can be represented by a set of heat and mass transfer equations describing the heat and moisture exchange within the product and between the product and air (Efremov, 2013). In various studies, thin-layer drying procedure is quite a reliable tool for evaluating the drying characteristics for a wide range of products (Akpinar *et al.,* 2003; Akgun and Doymaz, 2005; Trujillo *et al.,* 2007). Mathematical modelling of thin layer drying is critical for managing operating conditions during drying and for predicting the performance of a drying process (Fudholi *et al.,* 2011).

Thin layer drying generally means that drying is done as a single layer of slices or sample particles (Akpinar *et al.,* 2006). The categories of thin layer drying models currently being applied in evaluation of the drying characteristics of food products include; empirical, theoretical and semi-theoretical models. For the semi-theoretical models and empirical, only external resistance to moisture movement from the product to the air is taken into account (Fortes *et al.,* 1981), while the theoretical model takes into account the resistance to movement of moisture from within the product (Suarez *et al,.* 1980). Theoretical models can be used at all process conditions as they clearly explain the drying behaviors of products. However many assumptions are made (McMinn, 2006), causing considerable errors. In deriving most semi-theoretical models, the use of Fick's second law of diffusion is very common in literature. However, the validity of these models is only within the experimental conditions applied (Fortes and Okos, 1980). Similar to the semi-theoretical models, empirical models are strongly dependent on the drying conditions. However, information given on the drying behavior of the material is limited (Keey, 1972).

The drying rate of a food product describes the rate of conversion of moisture to vapor by evaporation and is dependent on the pressure gradient existing between the product and air due to an established temperature gradient (Ahmad *et al.,* 2017). Conversely, the rate of internal moisture transfer within a material during drying is described by an effective diffusivity (D_{eff}). It depends on the product's moisture content, temperature of the drying air, and the physical nature of the solid. The temperature and moisture content dependence of moisture diffusivity has been verified for various products (Zogzas *et al.,* 1996). Generally, the properties of agricultural products, such and moisture diffusivity are also required for the ideal dryer design and operation (Aghbashlo *et al.,* 2008).

Currently, there are many researches reporting on drying modelling and moisture diffusivity of different products as influenced by drying temperature and thickness of the product (Akgun and

Doymaz, 2005; Shiby and Mishra, 2007; Jena and Das, 2007; Doymaz, 2007). However, similar reports on beef drying temperatures encountered during solar drying (30-60 °C) are limited. Trujillo *et al.* (2007) used different drying methods to experimentally determine the moisture diffusivity of beef with temperatures ranging between 6.6 and 40.4 °C whereas Chabbouh *et al.* (2011), examined beef dehydration during the salting and drying processes of Kaddid meat's production. In the present study, drying curves were generated from experimental data of beef drying processes at different temperatures and sample thicknesses. Some selected semi-theoretical models were used to simulate the moisture removal behaviour of beef and the suitability of the models for characterizing the drying process was investigated. Influence of drying temperature and sample thickness on the effective moisture diffusivity of beef was also assessed.

3.2. MATERIALS AND METHODS

3.2.1. Sample collection and preparation

Meat (beef) of high microbial quality from the round of the hind quarter of an inspected male carcass was purchased from a local slaughter house in Nairobi, Kenya. Trimming of excess fat was done to prevent rancidity during drying. It was then cleaned and kept in a cold room for 48 h at 5 °C before experiments so that the storage conditions would be kept the same for all samples prior to drying. The meat was cooled overnight at 0 °C to obtain enough consistency for cutting and cut along its fibers' direction into strips of 100 mm long, 30 mm wide and different thicknesses (2.5, 5.0, 7.5 and 10 mm). For determination of the sample's initial moisture content, the oven method was used at 105 °C (AOAC, 2005; method 967.08).

3.2.2. Drying apparatus

Drying was done using a bench top cabinet dryer "Hohenheim HT mini" (*Innotech-ingenieursgesellschaft* GmbH, Altdorf, Germany) containing six perforated trays (420 x 440 mm each). The cabinet drier has a fan for air circulation and an exhaust flap that opens and closes to release exhaust air and attain maximum heating respectively. Heating power was provided by a heater 1.5-3 kW that was connected to a thermostat for automatic switching on and off. The dryer operates using application of the over current principle in which inlet air splits and moves between the trays and over all the layers of beef. This in combination with a registered profiled layout of the trays ensured the desired uniform air distribution inside the drying chamber. The dryer was started and the set temperature attained before each drying run.

3.2.3. Experimental design

The drying of beef samples was done at temperatures of 30, 40, 50, and 60 °C and airflow set at a constant voltage of 24 V. For each drying run, about 220 g of the meat pieces with varying slice thicknesses were placed as a single layer on the perforated trays. The trays and sample weights were noted before being inserted into the drier. To ensure uniform drying conditions, all trays were inserted into the dryer. As drying progressed, the trays were removed from the cabinet dryer at every 15 min interval and weighed using an electronic balance (ESA 600, Salter Brecknell, UK) before being returned to the dryer, ensuring the weighing process was done within 1 min. The experiments were repeated 3 times until the dried products had between 10–20% moisture contents (dry weight basis). This is the range of moisture content for traditional dried meat products of tropical countries (Kalilou *et al.*, 1998) which was similar to results found for critical moisture content for safe drying of beef (Chapter 2), within the experimental temperature range. The dried beef was allowed to cool and then packaged in low-density polyethylene (LDPE) bags.

3.2.4. Mathematical modelling

During the drying process, the moisture content of beef samples was determined as shown in the following equation:

$$M_t = \frac{(W_0 - W) - W_1}{W_1} \tag{3.1}$$

where M_t is the product's moisture content (g water/100 g dry matter or % dry weight basis(dwb)) at time t, W_0 is weight of sample before drying (g), W is the amount of evaporated moisture (g), and W_1 is the sample's dry matter content (g).

Drying curves were represented as moisture content against time and drying rate (DR) against moisture content graphs. The drying rate (DR) of beef slices was determined using the following equation:

$$DR = \frac{M_t - M_{t+\Delta t}}{\Delta t} \tag{3.2}$$

where $M_{t+\Delta t}$ is the moisture content at time 't+Δt' (% dwb) and t is time (min).

To the beef experimental data, Fick's diffusion equation was applied as shown below.

$$MR = \frac{M_t - M_e}{M_0 - M_e} \tag{3.3}$$

where *MR* represents the dimensionless moisture ratio; M_e is equilibrium moisture content (% dwb); M_t is moisture content at time t (% dwb) and M_0 is the initial moisture content (% dwb).

The value of M_e is relatively smaller, compared to values of M_t and M_0 (Menges and Ertekin, 2006), so the equation can be reduced to;

$$MR = \frac{M_t}{M_0} \tag{3.4}$$

The experimental data were presented as moisture ratio vs drying time graphs and fitted into five moisture ratio equations shown in Table 3.1.

Table 3.1: Mathematical models fitted to the drying data

Model name	Equation	References
Newton	$MR = \exp(-kt)$	(Fudholi *et al.*, 2011)
Logarithmic	$MR = a\exp(-kt) + c$	(Chandra and Singh, 1995)
Page	$MR = exp(-kt^n)$	(Page, 1949; Doymaz, 2004)
Henderson and Pabis	$MR = a\exp(-kt)$	Henderson and Pabis, 1961)
Two-term exponential	$MR = aexp(-kt) + (1-a)exp(-kat)$	(Sharaf-Eldeen *et al.*, 1980)

where *t* is time (min), *k* is the drying rate constant (min^{-1}) and *a*, *n* and *c* are drying constants.

3.2.4.1. Statistical analysis

Drying data analysis was done by using Minitab (Version 17.0, Minitab Inc., USA) software package and Excel 2008 (Microsoft Corporation, USA). Nonlinear regression was done based on the Gauss-Newton algorithm in order to estimate the model parameters. The model's fitting quality to the experimental data was assessed using the coefficient of determination (R^2) (Equation 3.10) calculated numerically by Excel and the standard error of the regression (standard error of estimate) (Equation 3.11) generated by Minitab. The ideal value of SEE is "zero", and a small value means that the data points fall closer to the curved fitted line (Borah *et al.*, 2015). For evaluation of goodness of fit of the experimental data to the models a low SEE value and a high R^2 value were taken (Basunia and Abe, 1999).

$$R^2 = \frac{\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,avg})^2}{\sum_{i=1}^{N}(MR_{exp,i} - MR_{exp,avg})^2}) \tag{3.10}$$

$$\text{SEE} = \sqrt{\frac{\sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})^2}{N}} \tag{3.11}$$

where $MR_{pre,i}$ is the predicted moisture ratio; $MR_{exp,i}$ is the ith experimental moisture ratio; $MR_{exp,avg}$ is the average experimental moisture ratio and N is the number of observations.

3.2.5. Effective moisture diffusivity (D_{eff}) determination

The drying process of most food materials has been described using Fick's second law of diffusion (Saravacos and Charm, 1962) in which the drying process occurs in the falling rate period (Wang and Brennan, 1992) as given below:

$$\frac{\partial M}{\partial t} = \nabla[D_{eff}(\nabla M)] \tag{3.12}$$

where effective moisture diffusivity (m^2/s) is given by D_{eff} (the term used to represent all moisture transport mechanisms within a sample), t is time (s) and M is the local moisture content (% dwb).

Crank, (1975) gives the solution of Fick's second law as shown in Equation 3.13, considering, uniform initial moisture distribution, constant moisture diffusivity and infinite slab geometry (Ahmad *et al.*, 2017).

$$MR = \frac{8}{\pi^2}\sum_{N=0}^{\infty}\frac{1}{(2n+1)^{2}}\exp\left(-\frac{(2n+1)^{2}\pi^2 D_{eff}t}{4L^2}\right) \tag{3.13}$$

where n represents a positive integer and L the slab's half thickness (m).

Only the first term of Equation 3.13 is normally applied, giving:

$$MR = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{eff}t}{4L^2}\right) \tag{3.14}$$

The slope of a normalized plot of experimental moisture ratio, ln (MR) vs time (s) can be used to obtain the D_{eff} of a sample, for corresponding temperature data using the following equation (Akpinar, 2006):

$$D_{eff} = \frac{-slope\ 4L^2}{\pi^2} \tag{3.15}$$

3.3. RESULTS AND DISCUSSION

3.3.1. Effect of air temperature on beef drying curves

The average moisture content of fresh beef was 328.69 % dwb and drying time for all the beef samples ranged between 2.5 and 30 h. Moisture content vs time graph for 2.5 and 5.0 mm thick beef samples are shown in Figures 3.1 and 3.2 respectively. To reach the desired moisture contents, drying time was 535, 345, 275 and 150 min at 30, 40, 50 and 60 °C, respectively (Figure 3.1).

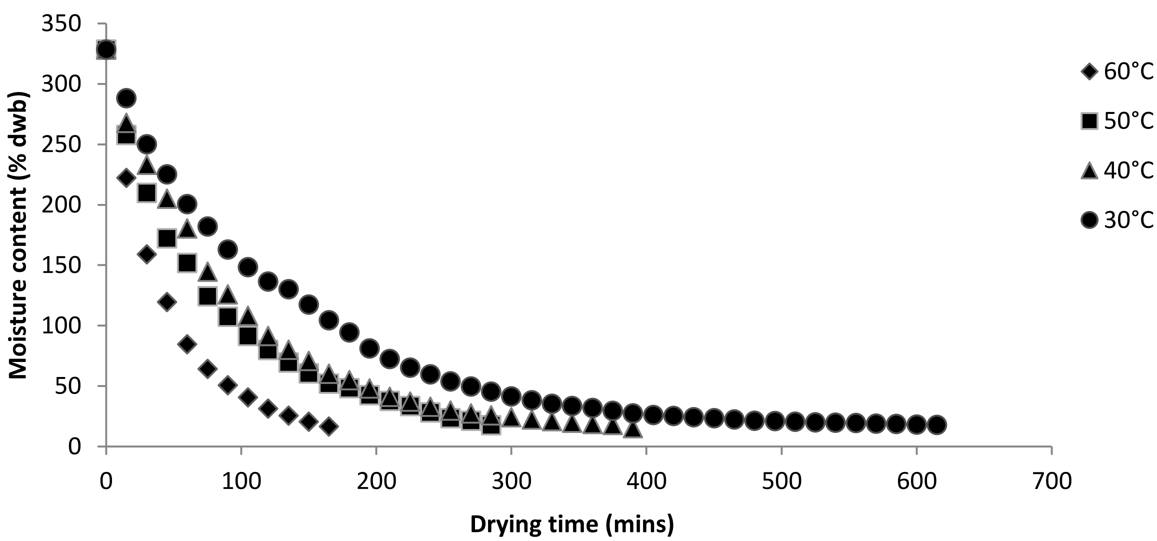

Figure 3.1: Drying curve of beef (2.5 mm thick slices) at different temperatures.

The drying process was enhanced by increasing the drying temperature within this temperature range, thus shortening the time of drying. The reduction in time with increasing temperature is attributed to increased thermal energy which results in faster transfer of water molecules within the meat (Maskan *et al.*, 2002). The higher temperatures also create large water to vapor pressure deficit, one of the driving forces for moisture transfer externally: from the surface of the meat to the air (Prabhanjan *et al.*, 1995). Comparable results have been reported for drying curves of other food materials (Mwithiga and Olwal, 2005; Speckhahn *et al.*, 2010). The relationship between temperature and drying time still followed the same trend when the thickness of the meat was increased to 5.0 mm (Figure 3.2).

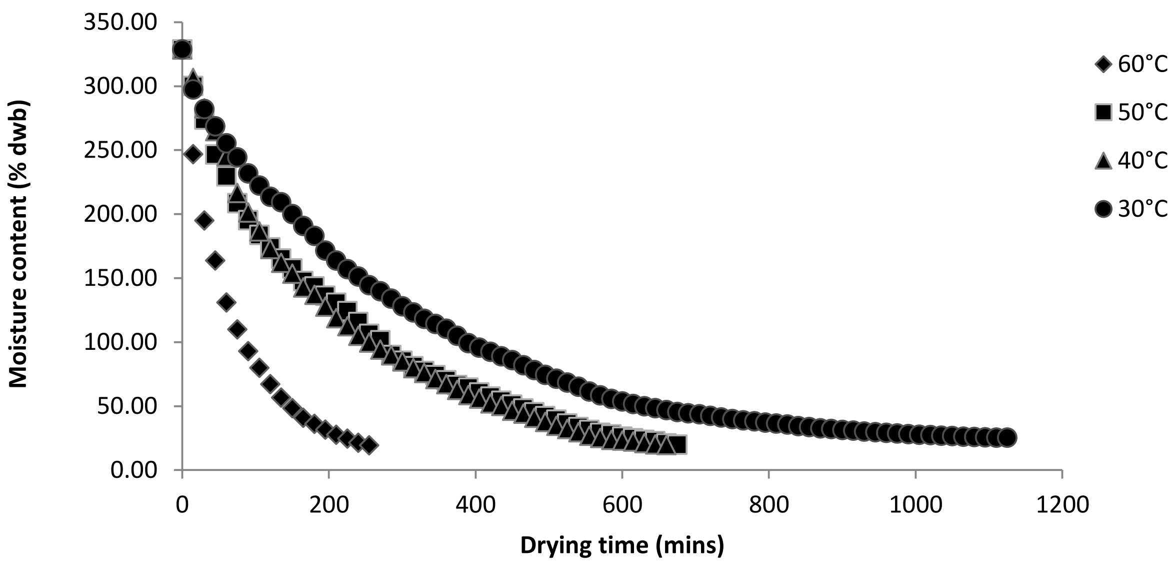

Figure 3.2: Drying curves of beef (5.0 mm thick slices) at different temperatures.

The lowest temperature effect on reduction of drying time was between 40 and 50 °C which resulted in overlapping of drying curves at this temperature range. When drying beef samples, Chabbouh *et al.* (2011) observed that after 30 min of dehydration, samples dried at 50 °C lost moisture slower than those dried at 40 °C. This was explained by the fact that during high temperature drying, rapid evaporation of moisture from the meat's surface allowed crust formation due to case hardening, presenting a high resistance to the transfer of moisture from within the meat thus lowering the drying rate (Mujjafar and Sankat, 2005). This effect could have been overcome at 60 °C due to change in internal meat structure as a result of changes in physico-chemical properties of beef. During heating, the different meat proteins denature at different temperatures, causing meat structural changes. Denaturation of connective tissue proteins occurs at 60-70 °C, which causes the longitudinal shrinkage of muscle fibres and connective tissue fibres, leading to larger extracellular voids (Tornberg, 2004). This, together with a higher heat transfer, could have promoted a faster moisture movement at 60 °C.

The drying rate vs moisture content curve for 10 mm thick beef slices at various temperatures is given in Figure 3.3.

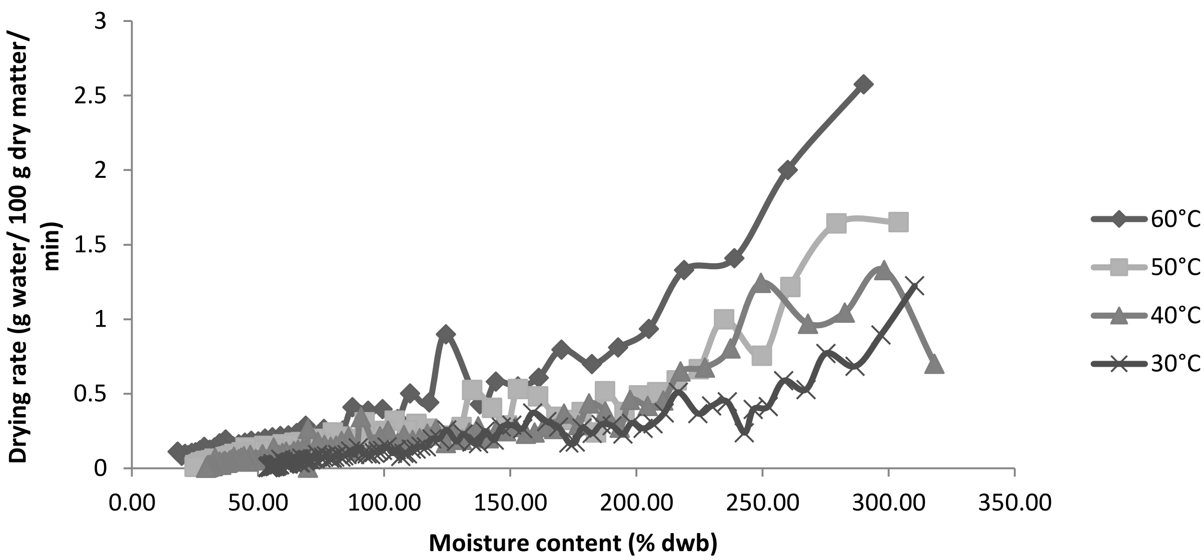

Figure 3.3: Drying characteristic curve of beef (10 mm thick slices) at different temperatures.

There was a continuous decrease in the rate of drying with decreasing moisture content and drying rate was highest at the highest temperature (60 °C). During beef drying, there was no constant drying rate period as the whole process occurred predominantly in the falling rate period. The lack of constant rate period may be explained by the fact that in the beginning of drying, the surface of meat dries out very quickly, generating a partial barrier which resists free moisture movement (Borah *et al.,* 2015). This means that the dominant physical mechanism controlling the transfer of moisture within the beef was diffusion, as obtained for most agricultural products (Aregbesola *et al.,* 2015).

3.3.2. Effect of thickness of beef samples on the drying curves

Effect of beef sample thickness on the drying curves is shown in Figures 3.4 and 3.5. Drying time increased with increased beef slice thickness (Figure 3.4). For thicker beef samples, the amount of water that needs to be moved from the center of the meat to its surface is more (Sa-Adchom *et al.,* 2011) thus increasing the time needed for drying the slice to the same level of moisture content (Saravacos and Charm, 1962).

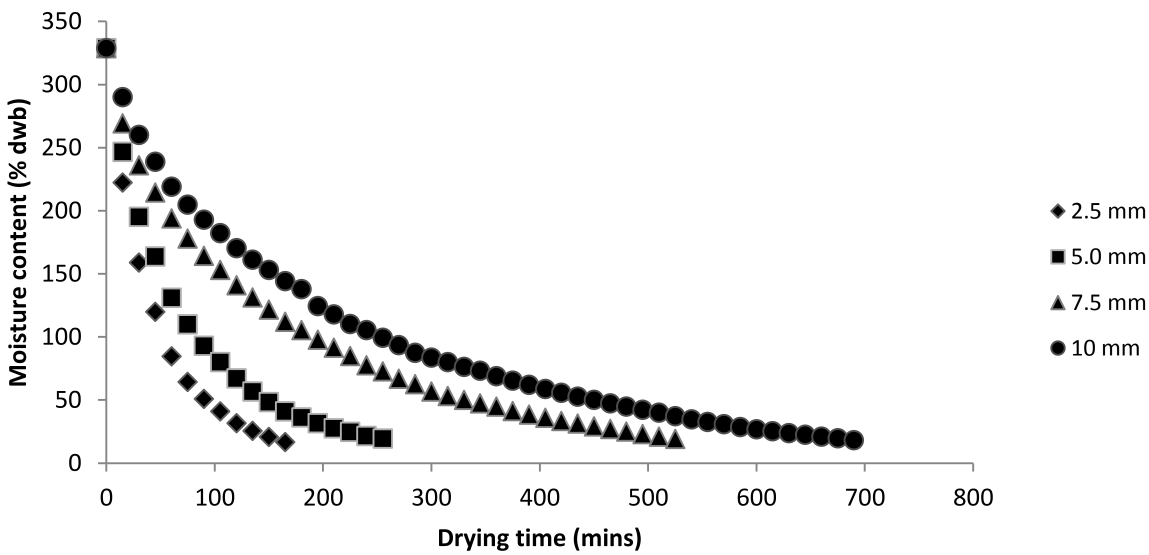

Figure 3.4: Drying curve for beef of different thicknesses at 60 °C.

The curve of drying rate vs moisture content at 60 °C (Figure 3.5) shows that beef with the smallest thickness value (2.5 mm) had the highest drying rate when compared to thicker samples. During the early stages of drying, drying rates were high and continuously decreased as moisture content decreased for all beef samples (Figures 3.3 and 3.5). With the continuous decrease of moisture content during drying, there is a diminishing presence of water in its free form: the moisture-food interactions become stronger (Shivhare *et al.*, 2004) causing a reduction in drying rate.

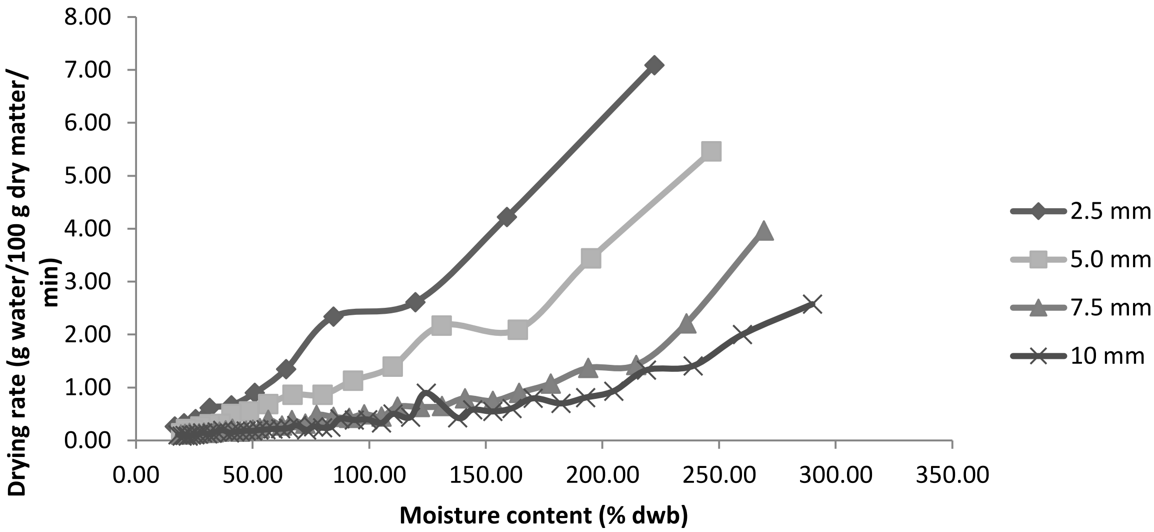

Figure 3.5: Drying characteristic curve for beef of different thicknesses at 60 °C

3.3.3. Mathematical modelling

The influence of temperature on the regression coefficients for five drying models was represented by the experimental results of 5.0 mm thick beef slices (Table 3.2). To evaluate the effect of slice thickness, experimental results for beef samples dried at 40 °C were randomly selected (Table 3.3). Specific model constants and statistical parameters (R^2 and SEE), for assessing the goodness of fit of each of the selected drying models are given in Tables 3.2 and 3.3. Increasing temperature enhanced the rate of drying (Table 3.2) as indicated by the k values for the two-term exponential and the page models. Increasing beef slice thickness reduced the drying rate (Table 3.3) and the k values decreased for each of the drying models.

All the five drying models indicated a good fit as they gave coefficient of determination (R^2) values greater than 0.99 at all drying conditions (Tables 3.2 and 3.3). The models that gave the lowest SEE and the highest R^2 values were the Page and two-term exponential models and were therefore chosen as the most appropriate models for simulating the drying kinetics of beef slices dried at 40 °C and of 5 mm thickness.

Table 3.2: Regression coefficients of the drying models for 5.0 mm thick beef slices

	temp	Statistical parameters		Model constants			
Model	(°C)	R^2	SEE	k(min^{-1})	a	n	c
Newton	30	0.9977	0.0280	0.0030			
	40	0.9967	0.0197	0.0047			
	50	0.9900	0.0310	0.0045			
	60	0.9944	0.0333	0.0141			
Henderson and Pabis	30	0.9977	0.0184	0.0028	0.9244		
	40	0.9967	0.0171	0.0045	0.9662		
	50	0.9943	0.0210	0.0042	0.9239		
	60	0.9944	0.0280	0.0131	0.9387		
Two-term exponential	30	0.9973	0.0135	0.0074	0.3049		
	40	0.9986	0.0101	0.0086	0.3980		
	50	0.9984	0.0101	0.0238	0.1602		
	60	0.9991	0.0102	0.0452	0.2438		
Page	30	0.9978	0.0116	0.0075		0.8489	
	40	0.9983	0.0110	0.0080		0.9044	
	50	0.9975	0.0125	0.0111		0.8388	
	60	0.9995	0.0064	0.0331		0.8089	
Logarithmic	30	0.9987	0.0088	0.0033	0.9064		0.0486
	40	0.9973	0.0137	0.0051	0.9504		0.0354
	50	0.9944	0.0187	0.0047	0.9063		0.0364
	60	0.9973	0.0148	0.0163	0.9119		0.0597

where R^2 and SEE are coefficient of determination and standard error of estimate respectively; k is the drying rate constant (min^{-1}) and a, n and c are drying constants.

However, for the whole range of experimental drying data (30-60 °C) and (2.5-10 mm thickness), Page model had the best fit. The goodness of fit of Page model for characterizing the meat drying process has also been shown by Ikonic *et al*. (2012).

Table 3.3: Regression coefficients of the drying models for beef dried at 40 °C

	Meat thickness	Statistical parameters	Model constants

Model	(mm)	R^2	SEE	k(min^{-1})	a	n	C
Newton	2.5	0.9974	0.0213	0.0102			
	5.0	0.9967	0.0197	0.0047			
	7.5	0.9898	0.0516	0.0034			
	10	0.9918	0.0426	0.0022			
Henderson and Pabis	2.5	0.9961	0.0191	0.0098	0.9652		
	5.0	0.9967	0.0171	0.0045	0.9662		
	7.5	0.9769	0.0367	0.0028	0.8510		
	10	0.9860	0.0284	0.0019	0.8853		
Two-term exponential	2.5	0.9968	0.0165	0.1255	0.0748		
	5.0	0.9986	0.0101	0.0086	0.3980		
	7.5	0.9933	0.0311	0.0065	0.2346		
	10	0.9961	0.0197	0.0046	0.2060		
Page	2.5	0.9976	0.0137	0.0169		0.8943	
	5.0	0.9983	0.0110	0.0110		0.9044	
	7.5	0.9944	0.0164	0.0088		0.7140	
	10	0.9967	0.0131	0.0063		0.7723	
Logarithmic	2.5	0.9990	0.0088	0.0112	0.9505		0.0384
	5.0	0.9973	0.0137	0.0051	0.9504		0.0354
	7.5	0.9932	0.0179	0.0039	0.8468		0.0719
	10	0.9937	0.0182	0.0025	0.8634		0.0687

where R^2 and SEE are coefficient of determination and standard error of estimate respectively; k is the drying rate constant (min-1) and a, n and c are drying constants.

Figures 3.6 and 3.7 give fitted line plots for moisture ratio against time for predicted and experimental data by the Page and two-term exponential models respectively, with the Page model showing a visually good fit.

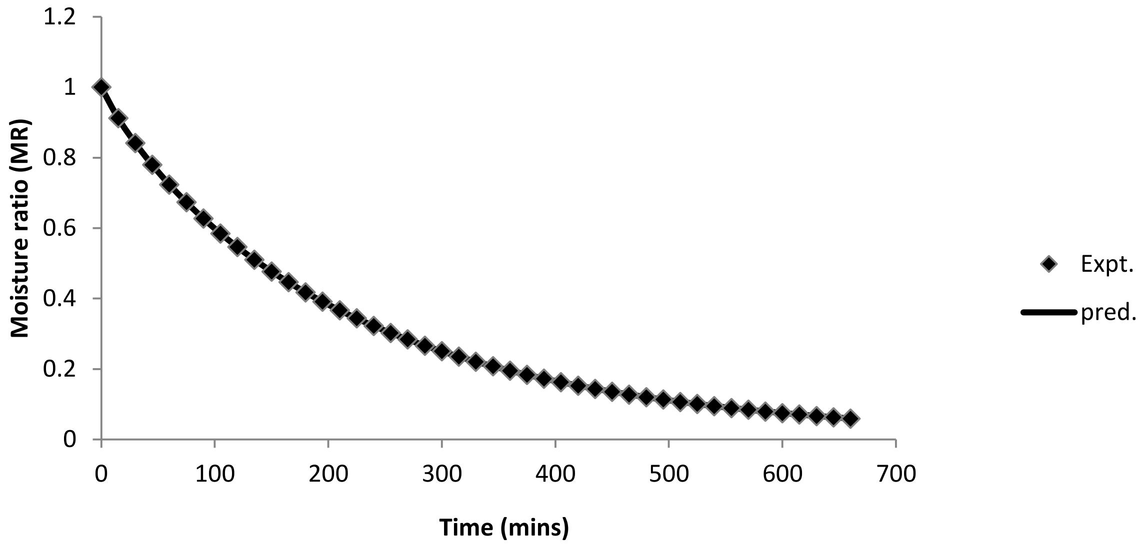

Figure 3.6: Page model fitting for 40 °C and 5.0 mm slice thickness

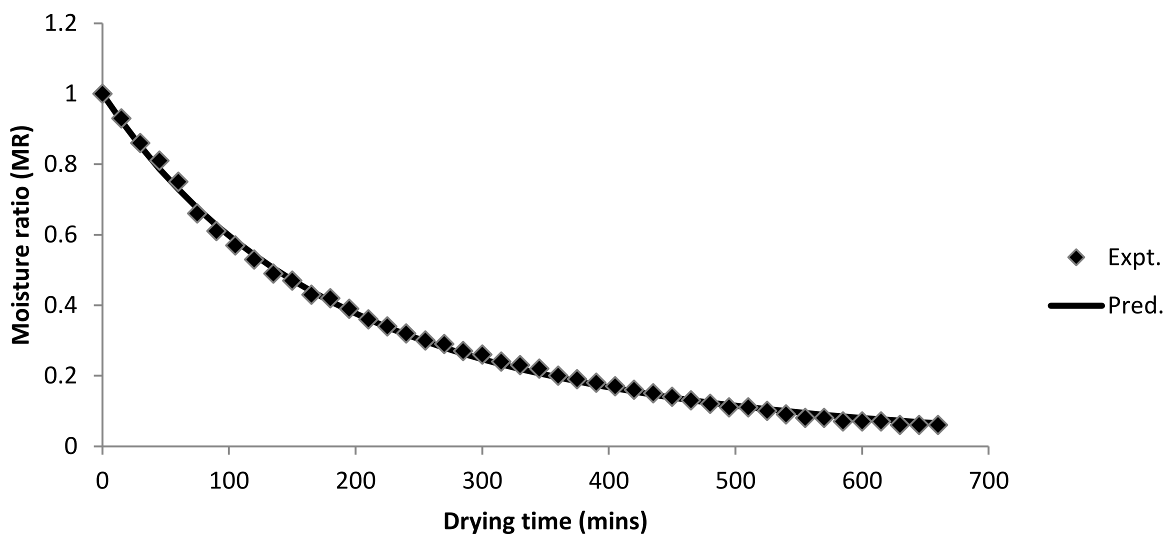

Figure 3.7: Newton model fitting for 40 °C and 5.0 mm slice thickness

The efficiency of the Page model for evaluating the drying kinetics of beef was further indicated by plotting a curve of predicted moisture ratios vs observed moisture ratios for 5.0 mm thick slices (Figure 3.8). A good fit for the experimental drying data was given by the predicted model, as indicated by the linear nature of the curve at 45° slope from the origin (Tulek, 2011).

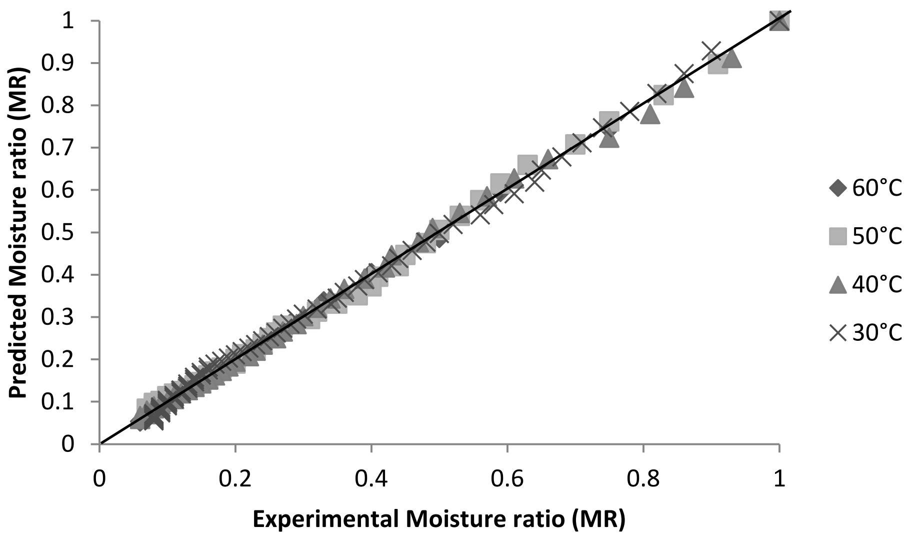

Figure 3.8: Comparison of predicted MR with experimental MR by page model for beef of 5.0 mm thickness

3.3.4. Effective moisture diffusivity (D_{eff})

Figure 3.9 shows the effect of temperature on the linear relationship between logarithmic moisture ratio vs time for 2.5 mm thick beef slices.

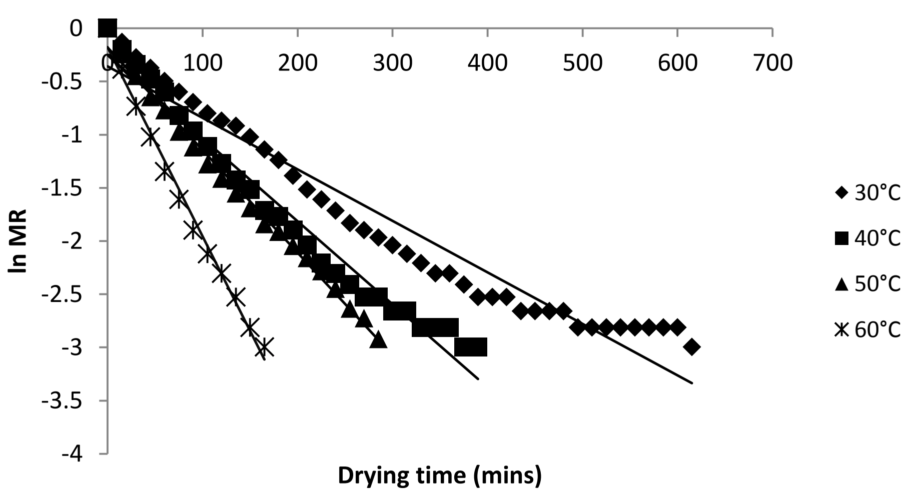

Figure 3.9: Logarithmic moisture ratio vs drying time graph for beef of 2.5 mm thickness

The values of D_{eff} for this study were within the standard range (between 10^{-11} to 10^{-9} m^2/s) obtained for most food products (Zogzas *et al.,* 1996) and could be compared to 1.20 x 10^{-11} to

1.15 x 10^{-10} m^2/s for meat products during drying under different conditions (Gou *et al.*, 2003; 2004). From the results, increasing temperature as well as slice thickness increased the D_{eff} values. Comparable results have been described for a number of food products (Ramaswamy and Van Nieuwenhuijzen, 2002; Jaya and Das, 2003; Akgun and Doymaz, 2005).

Table 3.4: Influence of drying temperature and slice thickness on the effective moisture diffusivity of beef.

Beef thickness (cm)	Drying temperature (°C)	D_{eff} x 10^{-10} (m^2/s)	R^2 (ln MR vs time graph)
0.25	30	0.4234	0.9471
	40	0.6987	0.9742
	50	0.8654	0.9936
	60	1.5964	0.9908
0.5	30	0.8385	0.9755
	40	1.5265	0.9975
	50	1.4190	0.9966
	60	3.8269	0.9958
0.75	30	0.8224	0.8624
	40	1.5480	0.9159
	50	2.4671	0.9836
	60	4.0151	0.9954
1.0	30	1.4620	0.9400
	40	2.3220	0.9745
	50	3.0950	0.9835
	60	5.5899	0.9967

where D_{eff} is effective moisture diffusivity; R^2 is the coefficient of determination.

A higher drying temperature increased thermal energy and subsequently resulted in high moisture diffusivity due to the increased activity of water molecules (Shi *et al.*, 2008). Nguyen and Price (2007), attributed the increase in diffusivity with thickness of a material to the edge effect (side way diffusion) of thicker slices. The diffusion model used in this study, assumed that diffusion took place from inside to the surface of the slab from one direction. This assumption was more applicable for thinner slabs for which the edge effect was negligible thus giving lower moisture diffusivity values. The diffusion model fit the drying experimental data better at higher temperatures, as shown by the high values of R^2 (Table 3.4) and the goodness of fit of the curve at 60 °C compared to 30 °C (Figure 3.9). This could be due to change in boundary conditions with change in temperature, particularly at lower temperatures. At lower temperatures, the drying rate is partly controlled by surface resistance due to the slower drying at the surface. At higher temperatures, diffusion within the meat largely controls the movement of water as the surface dries up more quickly (Trujillo *et al.,* 2007). Therefore, the assumption of negligible external resistance for the diffusion model was more applicable at higher temperatures.

3.4. CONCLUSIONS

Drying temperatures of 40-60°C in a cabinet dryer is capable of reducing the moisture content of beef (0.25-1.0 cm) slice thickness to less than 20% (stable moisture content). Drying rates are much higher during the initial high moisture period and decreases continuously with time at all the drying conditions. For this study, all the drying models used adequately represent the drying behavior of beef. However, the Page model gives the best fit. Moisture diffusivity (D_{eff}) for beef increases with drying air temperature and sample thickness and range between 4.2337 x 10^{-11} and 5.5899 x 10^{-10} m^2/s.

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CHAPTER 4: EFFECT OF DRYING AIR TEMPERATURE AND SAMPLE THICKNESS ON THE PHYSICAL AND MICROBIOLOGICAL QUALITY OF DRIED BEEF

ABSTRACT

The aim of this study was to investigate the influence of cabinet drying air temperature (30-60 °C) and sample thickness (2.5-10 mm) on the quality characteristics of dried beef. The physical (colour, rehydration ratio/RR and texture) and microbial quality of beef samples were evaluated using standard procedures. There was a significant decrease ($p \leq 0.05$) in L^*, a^*, $b^*$and chroma/C^* colour values with increasing temperature and beef thickness, while change in thickness had no effect ($p > 0.05$) on the hue/H^* colour attribute. The RR was higher at 60 °C for 5-10 mm thick samples and decreased ($p \leq 0.05$) with increase in beef thickness. The firmness values increased with increase in temperature from 30 to 50 °C, decreased at 60 °C and were significantly lower ($p \leq 0.05$) at 2.5 mm beef thickness. The total viable counts (TVC) and *Staphylococcus aureus* numbers in beef dried at 30 and 40 °C were higher than that of fresh beef, whereas drying at 60 °C significantly ($p \leq 0.05$) reduced the microbial numbers.

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4.1. INTRODUCTION

Meat is the edible part of the skeletal muscle of an animal that was healthy before slaughter (CFDAR, 1990). It is preferred as protein source by most people throughout the world due to its distinct flavor and rich nutrient matrix. However, meat is highly perishable, and the lack of proper preservation techniques in the tropics has led to post-slaughter losses; excess meat gets wasted and cannot be kept to be used during food shortage. Sun drying has been practiced for several years and has been used by nomads and pastoralists to preserve meat during excess supply (FAO, 1995). However, it is no longer recommended due to lack of a steady heat source thus difficulty in controlling the drying process. It could also be very time-consuming, with a high risk of contamination from animals, insects, dust, and bacteria (Park *et al.*, 2002).

Convective hot-air dryers are normally used for the industrial processing of various agricultural products in most developing countries. These drying systems reduce food spoilage by sufficiently reducing water activity of products, thus inhibiting microbial growth. However, hot-air drying may result in changes to the physico-chemical quality of meat (FAO, 1995) with temperature being the most influencing factor. Most of the changes that take place in meat during drying are as a result of protein denaturation. Especially, denaturation of heme proteins as well as oxidation of myoglobin pigments which cause darkening of products (Haard, 1992). Protein denaturation also results in shrunken muscle fibers and reduced water holding capacity thus creating a harder and more compact tissue texture (Harris and Shorthose, 1988). These changes in physical structure as well as the chemical properties of meat, as a result determine its ability to rehydrate, or return to its original weight when immersed in water (Farkas and Singh, 1991).

Muscles of healthy animals are regarded as sterile, but the slaughtering and butchering process creates an opportunity for bacteria to colonize meat surfaces (Olaoye, 2011). The initial microbial load on the surfaces of meat to be dried is determined by the hygiene of the abattoir and the handling practices during butchering and slicing of strips for drying (Mothershaw *et al.,* 2003). Subsequently, the presence of microorganisms in the product determines both its shelf-life and safety. The pathogens of interest in fresh and frozen meat and meat products are; *Staphylococcus aureus, Salmonella spp Escherichia coli, Campylobacter spp, Listeria monocytogenes, Yersinia enterocolitica* and *Clostridium perfringens* (Mor-Mur and Yuste, 2010).

With an increase in demand for high quality dried products that retain their natural characteristics (Fernandes *et al*., 2011) and consumer expectation for minimally processed, convenient and safe food products, solar drying is gaining a lot of interest. However, in order to optimize the drying process in tropical solar drying conditions, information on dried beef quality in conditions close to that of the real process is needed. The process of beef dehydration during salting and drying at low temperature conditions and its effect on quality has been examined (Chabbouh *et al.,* 2011). Whereas pre-treatment by salting is a common practice for traditional dried meat products in Kenya (Gichure *et al.,* 2014), consumers increasingly require low salt or unsalted foods. Furthermore, dried unsalted meat is more suitable for use as an ingredient in new product development. The objective of the present study therefore, was to evaluate the influence of cabinet air drying temperatures and beef slice thickness on the color (L^*, a^*, b^*, H^* and C^*), texture, rehydration ratio and microbiological quality of the dried product.

4.2. MATERIALS AND METHODS

4.2.1. Sample collection and preparation

Meat (beef) of high microbial quality from the round of the hind quarter of an inspected male carcass was purchased from Dagoretti slaughter house, Nairobi, Kenya. Trimming of excess fat was done to prevent rancidity while drying. It was then cleaned and kept in a cold room at for 48 h 5 °C before start of experiments so that the storage conditions would be the same for all samples before drying. The meat was frozen overnight to obtain enough consistency for cutting and cut into thin strips of 100 mm long, 30 mm wide and varying thicknesses of 2.5, 5.0, 7.5 or 10 mm, along the direction of its fibers. Fresh beef had an average moisture content of 76.67% (wwb).

4.2.2. Experimental design

A bench top cabinet dryer "Hohenheim HT mini" (*Innotech-ingenieursgesellschaft* mbH, Altdorf, Germany) was used to carry out the drying processes at air temperatures of 30, 40, 50, and 60 °C and airflow generated by a fan which was set at a constant voltage of 24 V. For each drying run, about 220 g of the meat pieces with varying slice thicknesses were spread out as a single layer on perforated trays. The drying experiments were repeated 3 times at each temperature and slice thickness and dried to 10-20% moisture content (dwb), which corresponded to water activity value of less than 0.6 in the experimental temperature range (Chapter 2).

4.2.3. Colour determination

Colour measurements were performed at room temperature (25 °C) using a hand held tri-stimulus colorimeter (Minolta Chroma Meter CR-200, Minolta Co., Osaka, Japan) with an 8 mm diameter measuring area. Before the measurements, calibration of the instrument was done on the Hunterlab colour space system using a white reference tile ("$L*$" = 97.50, "$a*$" = - 0.60 and "$b*$" = 2.30) and a D65 illuminant source. For each sample three dried strips from each replicate were placed on a flat plate, and the tip of the colorimeter measuring head pointed at different areas on the surface of the sample, where eight consecutive measurements were taken. Determination of the $L*$, $a*$ and $b*$ colour coordinates was done according to the ISO/CIE standard color space system recommended by Commission Internationale de l'Eclairage (Joint ISO/CIE Standard, 2008). Where $L*$ represents the lightness or darkness ($L*$=0 is black and $L*$=100 is white), +$a*$ and -$a*$ represent the redness and greenness respectively whereas +$b*$and -$b*$ represent yellowness, and blueness respectively.

In addition, the hue-angle (h°) describing the hue colour ($H*$) and saturation index or chroma ($C*$), which describes the brightness or vividness of color, were determined as given in Equations 4.1 and 4.2 respectively according to AMSA, (2012) guidelines:

$$h^o = \tan^{-1}(\frac{b^*}{a^*}) \tag{4.1}$$

$$C^* = (a^{*2} + b^{*2})^{0.5} \tag{4.2}$$

4.2.4. Rehydration ratio assessment

To calculate the rehydration ratio, the dried sample was weighed, immersed in a hot water bath at 100 °C for 10 min, drained and reweighed. The rehydration ratio was then calculated as shown in Equation 4.3. The procedure was conducted in triplicate for each sample.

$$RR = \frac{M}{M_0} \tag{4.3}$$

where *RR* is the rehydration ratio, and *M* and M_0 are the sample weights after and before placing in the hot water bath, respectively.

4.2.5. Texture measurement

Texture measurements were done for dried beef using a TA.XT.*plus* Texture Analyzer (Stable Microsystems, Surrey, UK) with the Volodkevich bite jaws (HDP/VB*) fixture. This fixture comprises upper and lower jaws which are fitted to the load cell and Heavy Duty Platform. It performs an imitative test by simulating the action of an incisor tooth biting through food. A sample is positioned in the lower jaw and the compressive movement of the upper jaw shearing into the meat provides the biting action (Hansen *et al.*, 2004). The Volodkevich test was carried out at a deformation rate of 100 mm/min to give the maximum shear force (N). The pre-test-speed, test speed, and post-speed were fixed at 5.0 mm/s, 5.0 mm/s and 2.0 mm/s respectively, and the compression distance was set at 25%. Height calibration was 10 mm above the sample. Pieces of dried beef samples measuring 1 cm^2 (square cross-section), were compressed using a 50 kg load cell when placed parallel to the compression plate surface.

4.2.6. Microbial analysis

Meat samples (25 g) were put in sterile glass jars containing 225 ml of sterile 0.85% saline solution and mixed for approximately 2 min. Decimal serial dilutions were prepared.

Subsequently, 0.1 ml aliquots of each dilution were spread over the surface of plates in triplicates. For the different microbial groups, the incubation conditions and culture media used were: total viable count on pour plates of plate count agar (PCA) at 35 °C for 48 h-AOAC official method 966.23 (AOAC, 2000); *Staphylococcus aureus* on Baird-Parker agar at 35 °C for 48 h (ISO 6888-1:1999); *Salmonella* on Xylose-Lysine-desoxycholate (XLD) agar at 35 °C for 24 h (ISO 6579); *Enterobacteriaceae* on Violet Red Bile Glucose (VRBG) agar at 35 °C for 24 h (ISO 21528-1:2017) and *Listeria monocytogenes* on Listeria selective medium at 35 °C for 24 h (ISO 11290-1:2004). The results were expressed as Log_{10} colony-forming units per gram (log_{10} cfu/g) of dried meat.

4.2.7. Statistical analysis

In order to evaluate the effects of experimental variables (drying temperature and beef slice thickness) on beef quality parameters; a 4 x 4 factorial arrangement was used. The data were analysed using MINITAB version 16 software (Minitab Inc, Pennsylvania, USA). Analysis of variance (ANOVA) was done and the p-value used to establish significance of main effects and interaction between variables at $\alpha \leq 0.05$, $\alpha \leq 0.01$ or $\alpha \leq 0.001$. To determine differences between means, the experiments were designed as a single factor completely randomized design. The results were subjected to one-way ANOVA and differences in treatment means identified by Duncan's Multiple-range Test at $p \leq 0.05$ using GenStat Edition 13 software (VSN International Ltd, UK). All the experiments were replicated three times.

4.3. RESULTS AND DISCUSSION

4.3.1. Colour

Mean colour parameter values of fresh beef and samples dried at different experimental conditions are given in Table 4.1. The temperature and slice thickness effects on colour parameters are also given. Fresh beef had values of 32.70±2.10, 14.70±1.19, 7.74±0.64, 27.90±3.80 and 16.60±0.77 for *L**, *a**, *b**, hue (*H**) and saturation index/chroma (*C**) respectively (Table 4.1).

Table 4.1: Effect of drying temperature and sample thickness on beef colour parameters

		*L**	*a**	*b**	*H**	*C**
Fresh beef		32.70±2.10^{g}	14.70±1.19^{h}	7.74±0.64^{j}	27.90±3.80^{ab}	16.60±0.77^{h}
Dried beef						
temp (°C)	thickness (cm)					
30	0.25	26.20±3.50^{f}	8.88±2.00^{g}	4.10±2.08^{i}	25.00±6.56^{ab}	9.83±2.63^{g}
	0.50	25.70±1.78^{def}	5.78±1.52^{e}	2.85±1.48^{efg}	25.10±6.14^{ab}	6.47±1.99^{e}
	0.75	25.30±2.73^{cdef}	4.70±0.39^{d}	2.75±0.94^{ef}	30.00±8.36^{abc}	5.49±0.60^{d}
	1.00	23.60±0.68^{bcdef}	2.90±0.53^{c}	2.60±1.74^{ef}	38.60±12.47^{cd}	3.96±1.58^{b}
40	0.25	25.90±1.41^{ef}	7.69±1.56^{f}	3.72±1.38^{hi}	25.30±5.20^{ab}	8.58±1.91^{f}
	0.50	24.90±1.80^{bcdef}	4.56±1.17^{d}	2.37±0.75^{de}	28.00±9.82^{ab}	5.20±1.09^{cd}
	0.75	24.00±3.71^{abcde}	2.66±0.67^{bc}	1.08±0.30^{a}	22.20±4.25^{a}	2.87±0.70^{a}
	1.00	23.60±2.70^{abcd}	2.53±1.48^{bc}	1.54±0.74^{abc}	32.50±17.68^{bc}	3.05±1.47^{a}
50	0.25	25.90±2.31^{ef}	5.63±0.89^{e}	3.51±1.19^{ghi}	31.10±5.54^{abc}	6.66±1.35^{e}
	0.50	23.90±1.99^{abcde}	4.43±0.61^{d}	2.30±0.40^{cde}	27.60±5.02^{ab}	5.01±0.58^{cd}
	0.75	23.40±2.63^{abc}	2.50±0.52^{abc}	1.00±0.36^{a}	22.20±8.97^{a}	2.72±0.48^{a}
	1.00	22.40±1.91^{a}	2.25±0.82^{abc}	1.46±0.67^{ab}	33.30±13.32^{bc}	2.74±0.86^{a}
60	0.25	25.50±2.52^{cdef}	2.98±0.44^{c}	3.28±0.96^{fgh}	47.00±5.66^{de}	4.45±0.95^{bc}
	0.50	23.00±2.08^{ab}	1.79±0.74^{ab}	2.22±0.66^{bcde}	51.20±15.73^{e}	2.95±0.59^{a}
	0.75	22.70±3.08^{a}	2.01±0.71^{ab}	2.08±0.56^{bcde}	46.60±12.03^{de}	2.95±0.64^{a}
	1.00	22.40±2.02^{a}	1.66±0.77^{a}	1.76±0.64^{abcd}	46.50±14.97^{de}	2.49±0.79^{a}
Effect	temp	***	***	***	***	***
	thickness	***	***	***	NS	***
	temp x thickness	NS	***	NS	*	***

Means in the same column with the same superscripts are not significantly different at $P > 0.05$; treatment effects significant at *$p \leq 0.05$; ** $p \leq 0.01$; *** $p \leq 0.001$; NS not significant at $p > 0.05$.

Meat colour is one of the most important quality traits and can be affected by several factors including; pH, protein denaturation, and moisture content (Feiner, 2006). Drying temperature significantly affected ($p \leq 0.001$) all the colour variables increasing *H** and decreasing *L**, *a**, *b** and *C** (Table 1). Teixeira *et al.* (2011) reported similar results for air dried goat meat. Increasing beef thickness during drying significantly decreased the *L**, *a**, *b** and *C** colour parameters but had no effect ($p > 0.05$) on the *H** colour attribute.

The lightness (*L**) values of dried beef at all experimental conditions ranged from 22.40±2.02 to 26.20±3.50. The *L** value indicates the extent of browning of dried samples; a higher L* value showing less brown color of the product (Rahman *et al.*, 2002). The reduction of *L** values showed that drying at a higher temperature caused significant protein structural changes of meat samples (Lawrie, 1998). This could have been caused by the Maillard browning reactions resulting from the reaction between amine groups of muscle proteins and available reducing sugars in connective tissues during heat processing of meat products (Forrest *et al.*, 1975). The decrease in *L** values with meat thickness was as a result of the longer exposure of the beef to the drying medium due to the longer drying time, resulting in more browning of sugar-amine.

The redness (*a**) values of dried beef ranged from 1.66±0.77 to 8.88±2.00. The decrease in redness (*a**) values with temperature was significant ($p \leq 0.05$) at a lower meat thickness (2.5 mm). A significant interaction ($p \leq 0.001$) between drying air temperature and beef thickness on reduction of redness (*a**) and red intensity as noted by saturation index (*C**) was also observed (Table 4.1). The redness of meat is due to the presence of myoglobin, which is the most important meat pigment (Hedrick *et al.*, 1994). Surface discoloration in fresh meat is mostly as a result of metmyoglobin formation (Renerre, 1990), which is an oxidised form of myoglobin. The rate of myoglobin oxidation is greatly accelerated by temperature increase (Yin and Fautsman, 1993), causing a reduction in redness of meat.

The degree of browning during thermal drying as well as the source of variation in light scattering from the meat surface is represented by the *L**, *a** and *b** values (van Oeckel *et al.*, 1999). However, the *H** and *C** values, calculated from the CIE *a** and *b** values provide greater sensitivity than *L** *a** and *b** values alone (Little, 1975). Samples dried at lower temperatures had significantly lower ($p \leq 0.05$) hue colour values of compared to beef slices dried at 60 °C (Table 4.1). Hue (*H**) is the colour description as communicated in language (red, yellow, green, blue) (AMSA, 2012). Larger *H** values in meat indicate less red, more metmyoglobin formation and a more well-done cooked color (Howe *et al.*, 1982).

4.3.2. Rehydration ratio (RR)

Both temperature and sample thickness had significant ($p \leq 0.001$) effects on the rehydration ratio of beef whereas the interaction effect was not significant ($p > 0.05$) (Table 4.2). Rehydration refers to the process of moistening a dried product and is an indicator of cellular and structural disintegration occurring during dehydration (Rastogi *et al.*, 2000). Changes in rehydration ratio of beef samples of different thicknesses dried at different temperature conditions and are shown in Figure 4.1.

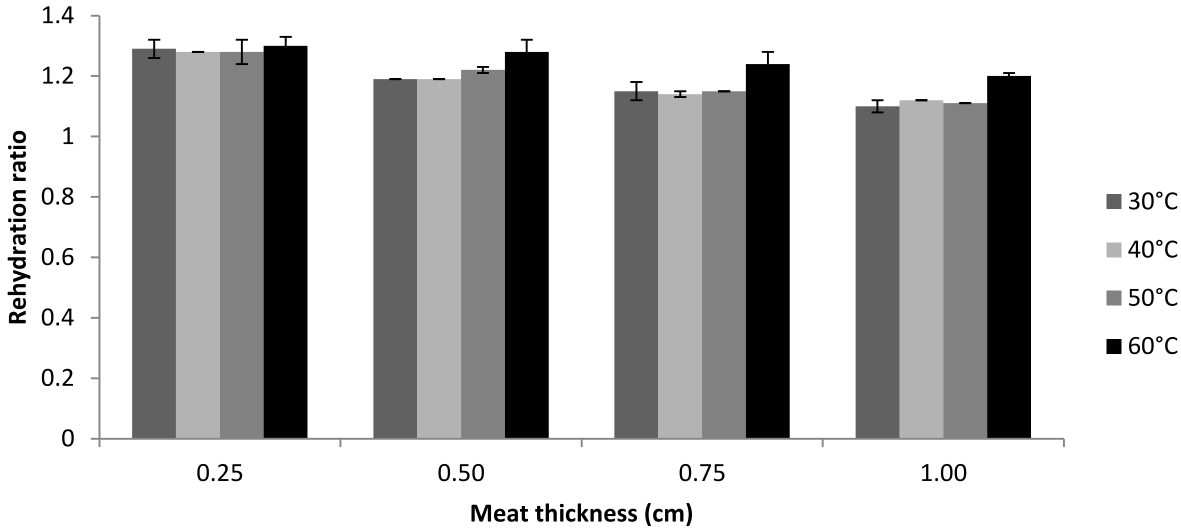

Figure 4.1: Rehydration Ratio for beef of different thicknesses dried at different temperatures.
Each value is expressed as mean ± standard deviation (n=3).

There was no significant difference ($p > 0.05$) in rehydration ratio for samples with 2.5 mm thickness at all the drying temperatures, whereas RR was significantly higher ($p \leq 0.05$) at 60 °C for dried beef with thicknesses of 5.0, 7.5 and 10 mm. The rate and extent of water uptake during rehydration of meat is greatly influenced by the cellular and structural arrangements in the food matrix since this provides the channels for transporting water to muscle fibers (Niamnuy *et al.*, 2014). During heating, denaturation of the different meat proteins occurs, causing structural changes in meat. These include; transverse and longitudinal shrinkage of muscle fibres, shrinkage and solubilization of connective tissue fibres, aggregation and gel formation of sarcoplasmic proteins and the destruction of cell membranes (Tornberg, 2005). The transverse shrinkage of muscle fibres occurs mostly at 40 to 60 °C, while the connective tissue fibres and the muscle fibres cooperatively shrink longitudinally at 60 to 70 °C, leading to larger extracellular voids (Tornberg, 2005). This, together with solubilization of connective tissues could explain the increased water uptake during rehydration of dried beef at 60 °C.

There was a significant decrease ($p \leq 0.05$) in rehydration ratio with increase in meat thickness at all drying temperatures (Figure 4.1). This may be explained by the fact that the moisture removal rate from meat with a higher thickness value was slower, thus increasing the drying time and exposure to high temperature. This enhanced denaturation of myofibrilar and collagenous connective tissue proteins, making them lose their water holding ability (Nathakaranakule *et al.*, 2007) and resulting in loss of ability to reconstitute faster.

Table 4.2: Temperature and thickness effects on rehydration ratio and beef firmness

Effects	Rehydration Ratio	Beef Firmness (N)
Temperature	***	***
Thickness	***	***
Temperature x Thickness	NS	***
r^2	0.86	0.93

*$P \leq 0.05$; ** $P \leq 0.01$; *** $P \leq 0.001$; NS not significant at $P > 0.05$

4.3.3. Texture

Figure 4.2 shows beef firmness (N) values as affected by drying temperature and sample thickness. Both simple effects and the interaction effect had a significant effect ($p \leq 0.001$) on the texture of beef (Table 4.2). However, there was no significant effect ($p > 0.05$) of temperature on firmness values at higher beef thicknesses (5 to 10 mm) and the effect of drying temperature was more pronounced at beef thickness of 2.5 mm. Texture is the functional and sensory indicator of the mechanical, surface and structural properties of foods perceived via the senses of vision, touch, kinesthetic and hearing. Its components include; hardness, firmness/softness, crispness, juiciness, mealiness/grittiness and toughness/fibrousness (Szczesniak, 2002).

The firmness values of dried beef increased with an increased temperature from 30 to 50 °C then decreased at 60 °C (Figure 4.2). Texture changes during processing are caused by complex chemical changes on the muscle fibers and connective tissue fibers. Davey and Gilbert, (1974) reported on the variation of texture within a temperature range of 40 to 75 °C and the effect of heat-induced denaturation of meat proteins at varying temperatures. Heating meat to around 50 °C increases its toughness, which has been attributed to myofibrillar denaturation (Bouton and Harris, 1972). The improved tenderness of meat at 60 °C is related to collagen denaturation (Bouton and Harris, 1981), although there has been speculations of effect of increased protolytic activity in beef muscles (Davey and Niederer, 1977) resulting in meat tenderization.

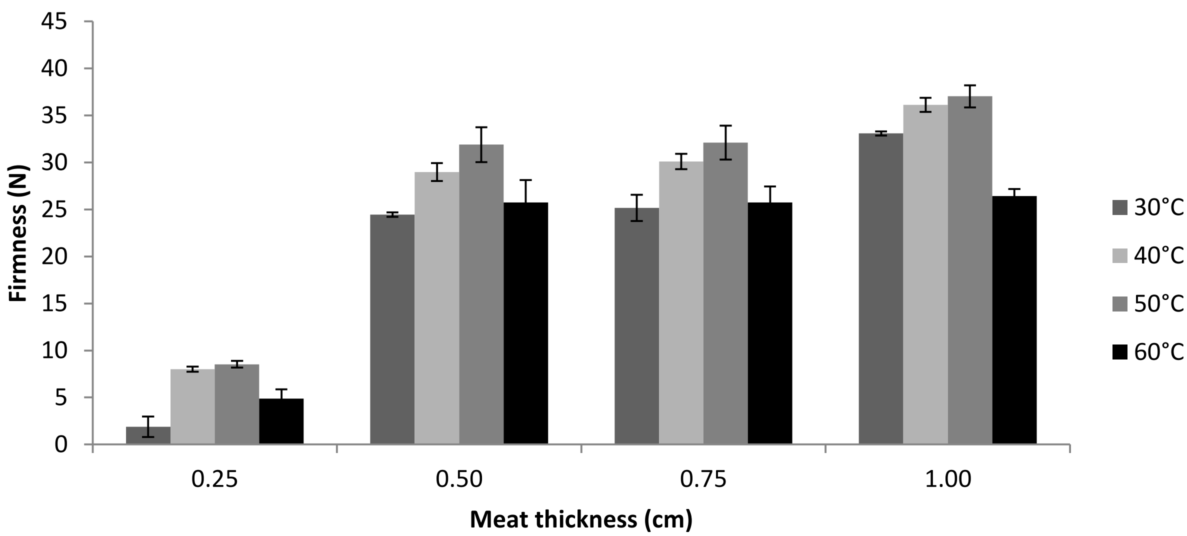

Figure 4.2: Firmness values for beef of different thicknesses dried at different temperatures.
Each value is expressed as mean ± standard deviation (n=3).

The Volodkevich firmness values were significantly lower ($p \leq 0.05$) at meat thickness of 2.5 mm. The longer drying time could have caused the thicker meat slices to be exposed to heat for longer; as a result, the muscle fibers were more shortened (Sa-adchom *et al.,* 2011) giving a much denser material and tougher meat. The size of the meat could also have influenced the firmness values due to the higher compression force required to deform thicker meat

4.3.4. Microbial quality

Table 4.3 shows the results obtained from the quantification of bacteria in the fresh and dried beef samples evaluated immediately after drying. No significant growth (< 2.00±0.00 $\log_{10}$ cfu/g) of *Enterobacteriacea* was observed, while *Salmonella* spp and *Listeria monocytogenes* were not detected in any of the samples. Generally *Enterobacteriaceae* and *Listeria* species are mostly good indicators of post-process contamination and hygiene of heat processed foods (FSA, 2001; Wang and Murianna, 1994).

Fresh beef had an aerobic plate count of 4.89±0.01 $\log_{10}$ cfu/g (Table 4.3). The beef samples used for drying were taken from chilled and frozen cuts, which could have enhanced microbial growth. Frozen and thawed meat usually require better hygiene and handling practices compared to unrefrigerated meat (Pham, 2004). This is due to the fact that thawing creates more favourable temperature conditions for microbial growth as it is a slower and less uniform process compared to freezing. The structural disarray caused by the freezing process, results in exudate formation during thawing. This nutrient dense moisture also provides an excellent medium where microorganisms can thrive (Leygonie *et al.,* 2012). The numbers of *Staphylococci* present in the fresh meat were high, 4.65±0.05 $\log_{10}$ cfu/g of beef (Table 4.3). These species are naturally found in humans and the high levels found in fresh meat was attributed to the fact that; during preparation of the meat samples for drying, they were excessively handled with the aim of ensuring uniform strips were prepared to reduce experimental error (Mothershaw *et al.,* 2003).

Table 4.3: Mean bacterial counts for fresh and dried beef samples

		Entero-Bacteriaceae	*Salmonella*	*Listeria mono Cytogenes*	TVC	*Staphylococcus aureus*
Fresh meat		<2.00±0.00	ND	ND	4.89±0.01^{e}	4.65±0.05^{d}
Dried Meat						
Meat thickness (cm)	Drying temp (^{0} C)					
	0.25	<2.00±0.00	ND	ND	6.04±0.01^{i}	5.99±0.01^{i}
30	0.50	<2.00±0.00	ND	ND	6.24±0.01^{j}	6.17±0.01^{j}
	0.75	<2.00±0.00	ND	ND	6.98±0.02^{k}	6.76±0.03^{k}
	1.00	<2.00±0.00	ND	ND	7.12±0.05^{l}	7.08±0.03^{l}
	0.25	<2.00±0.00	ND	ND	5.28±0.01^{f}	5.13±0.08^{f}
40	0.50	<2.00±0.00	ND	ND	5.37±0.10^{g}	5.23±0.01^{f}
	0.75	<2.00±0.00	ND	ND	5.69±0.01^{h}	5.37±0.01^{g}
	1.00	<2.00±0.00	ND	ND	5.74±0.03^{h}	5.55±0.05^{h}
	0.25	<2.00±0.00	ND	ND	5.27±0.01^{f}	5.01±0.06^{e}
50	0.50	<2.00±0.00	ND	ND	5.21±0.01^{f}	4.92±0.04^{e}
	0.75	<2.00±0.00	ND	ND	4.19±0.02^{c}	4.00±0.06^{b}
	1.00	<2.00±0.00	ND	ND	4.10±0.02^{b}	3.98±0.03^{ab}
	0.25	<2.00±0.00	ND	ND	4.55±0.03^{d}	4.46±0.00^{a}
60	0.50	<2.00±0.00	ND	ND	4.15±0.04^{bc}	3.89±0.02^{a}
	0.75	<2.00±0.00	ND	ND	3.48±0.01^{a}	<2.00±0.00
	1.00	<2.00±0.00	ND	ND	<2.00±0.00	<2.00±0.00
	Temp.				***	***
Effects	Thickness				***	***
	Temp. x Thickness				***	***

Microbial counts expressed as $\log_{10}$ cfu/g; ND not detected; means in the same column with the same superscripts are not significantly different at P> 0.05; treatment effects significant at *p ≤ 0.05; ** p ≤ 0.01; *** p ≤ 0.001; NS not significant at p > 0.05.

The effect of temperature, beef slice thickness and the interaction between the variables on the TVC and numbers of *Staphylococci* on dried beef samples was significant (p ≤ 0.001) (Table 4.3). The TVC counts in beef dried at 30, 40 and 50 °C (at 2.5 and 5.0 mm meat thicknesses) were significantly higher (p ≤ 0.05) than that of fresh beef. The increase in bacterial counts could be explained by the influence of low temperature drying for a longer time. The thickness of meat determines the duration of drying and therefore the length of exposure of microorganisms to the drying medium. The *Staphylococci* were also resistant to drying at these low temperatures (30-50

°C); their numbers were highest (7.08±0.03 $\log_{10}$ cfu/g) for beef samples with 10 mm slice thickness, dried at 30 °C (Table 4.3). This suggests that the *Staphylococci* continued to increase in numbers during the initial stages of low temperature drying, until water activity (a_w) was reduced to below about 0.86 (Dave and Ghaly, 2011).

Staphylococcus aureus are common food borne pathogens that can cause food poisoning and produce sufficient enterotoxin with minimum number of cells of 7.00 $\log_{10}$ cfu/g (Mossel and van Netten, 1990). Subsequently there could be a potential health risk due to the high numbers detected. *Staphylococci* can grow at a temperature range of 6.70 to 45.40 °C with the optimum being 37 °C. This temperature is also optimal for staphylococcal enterotoxin (SE) production (Baird-Parker, 1971). In general, drying at the lowest temperature significantly increased ($P \leq 0.05$) the microbial flora approximately 2–3 log cycles and drying at 60 °C was the most effective drying process for reducing microbial numbers.

4.4. CONCLUSIONS

Increasing the drying temperature has a significant effect on all the colour parameters, increasing *H** and decreasing *L**, *a**, *b** and *C**. Increasing the meat thickness decreases *L**, *a** and *b** values. Drying of beef at 60 °C produces a product with the highest rehydration ratio compared to drying at lower temperatures. Rehydration ratio of dried beef decreases with increase in meat thickness at all drying temperatures. Firmness of dried beef increases with increase in temperature from 30 to 50 °C then decreases at 60 °C at a thickness below 5.0 mm but is not affected by temperature at higher thicknesses. The lowest firmness of dried beef occurs at a slice thickness of 2.5 mm. Drying at 60 °C is most effective in reducing bacterial numbers when compared to lower drying temperatures.

CHAPTER 5: MATHEMATICAL MODELLING OF THE SOLAR TUNNEL DRYING KINETICS OF BEEF

ABSTRACT

Solar drying can be considered as an elaboration of sun drying and an efficient system of utilizing solar energy. This study focused on the experimental analysis on drying kinetics of beef dehydrated in a solar tunnel dryer compared to drying in the open sun. During the drying process, the ambient air conditions and the parameters of drying air were monitored. Experimental drying curves were then determined. The obtained drying data were fitted to five semi-theoretical models and their constants evaluated by non-linear regression analysis. Validity of the models was assessed using the coefficient of determination (R^2), the reduced chi-square (χ^2), mean relative percent error (P) and root mean square error (E_{RMS}). Determination of effective moisture diffusivity of beef was also done. During the drying period, the ambient temperature, ambient relative humidity, inlet air velocity and solar radiation intensity were in the range of 21.3-38.9 °C, 48-69.5%, 0.02-0.18 m/s and 476.3-1000 W/m^2 respectively. Temperature profile along the tunnel dryer increased with increased solar radiation and decreased continuously at high moisture content of beef. Samples dried in the solar drier had a higher drying rate compared to sun dried beef samples whereas drying occurred predominantly in the falling rate period for both drying methods. The most suitable model for representing the drying characteristics of beef was the Page model. Effective moisture diffusivity varied from 2.282 10^{-10} to 2.536 x 10^{-10} m/s^2 for solar dried beef and was 1.775 x 10^{-10} m/s^2 for samples dried in the open sun. Compared to open sun drying, solar tunnel drying improved the quality of the drying process through reduction of drying time and realization of efficient performance and drying effectiveness.

5.1. INTRODUCTION

In Sub-Saharan Africa, the most consumed meat product is beef. Its production is highest in South Africa, Kenya, Egypt, Nigeria, Sudan and Morocco respectively (FAOSTAT, 2016). More than 50% of livestock population in Kenya is found in the arid and semi-arid lands under the pastoral production system, which provides the bulk of meat consumed in the country (Kahi *et al.,* 2006). However, due to lack of cold storage facilities and climatic conditions in these areas, it is essentially not possible to preserve meat or meat products for any length of time. Meat has a rich nutrient matrix and high water activity, thus highly perishable and can undergo deterioration from time to time. This can result in post-harvest losses which can be as high as 50% of the meat produced, leading to food insecurity and reduced profit margins to value chain actors in Kenya (Lewa, 2010).

It is therefore, necessary to adopt technologies which can effectively reduce the post-harvest losses by applying appropriate methods of post-harvest handling, processing and preservation. Some of the new meat preservation technologies that have been used in research include hot-air drying (Chabbouh *et al.,* 2011), superheated steam drying (Speckhahn *et al.,* 2010), vacuum drying (Arnau *et al.,* 2007) and freeze drying (Krokida *et al.,* 1998). However, due to their energy requirements, these technologies are not applicable and affordable to most farmers in the arid and semi-arid areas. Sun drying is commonly practiced in the developing countries as a method of meat preservation and is still preferred due to the use of solar energy which can serve as a sustainable energy source, is renewable and environment friendly (Xie *et al.,* 2011). During open sun drying, the surface of the drying material absorbs solar radiation, which is converted to heat and is conducted to the interior of the bulk. This leads to temperature increase of the drying product and provides energy for transfer of moisture to the air. Natural convection supported by wind energy, then removes the evaporated water (Kemp, 2012). However, the method, exposes the product to contamination by dirt, dust, insects and bacteria (Hii *et al.,* 2012) causing significant reduction of product quality.

Solar drying can be done as an alternative to open sun drying as it is a promising and attractive application of solar energy systems. This technology is suitable for use in the pastoral areas of Kenya as there is abundant supply of solar energy. Solar dryers are classified into two main groups based on the mode of air flow: forced convection and natural convection solar dryers (Ekechukwu and Norton, 1999). In a properly designed natural convection dryer, air current can be generated due to density gradient of the air along the dryer (Tesfamichael and Assefa, 2013). However, the long drying times as a result of the low air flow gives a low drying capacity of the natural convection dryers. Forced convection dryers require a power source for operating an external fan or blower to create air current within the dryer. The forced convection types of dryers include; solar tunnel driers, greenhouse type solar driers, indirect forced convection solar driers and roof integrated solar driers (Oosthuizen, 1996; Janjai, 2004).

Research on solar tunnel drying of food products in different regions of the tropics and subtropics has mostly covered experimental investigations on dehydration of fruits (Schirmer, *et.al*, 1996; Bala *et al.,* 2003; Elicin and Sacilik, 2005), vegetables (Sacilik, 2007; Sacilik *et al.*, 2006; Hossain and Bala, 2007) and fish (Bala and Mondol, 2001; Kituu *et al.,* 2010) and several mathematical models have been applied for simulating the drying kinetics of the products. However, work on experimental investigations on solar tunnel drying kinetics of beef is apparently not available in literature. The present study was therefore undertaken to evaluate the solar tunnel drying kinetics of beef, while comparing the experimental data to data obtained from open sun drying as the control.

5.2. MATERIALS AND METHODS

5.2.1. Solar tunnel dryer

Installation of the Hohenheim type solar tunnel dryer was done at Ewaso Ng'iro North Development Authority (ENNDA) premises, Isiolo county, Kenya. The dryer (18 m long, 1.96 m wide and the transparent cover inclined 15° to the horizontal) was placed horizontally on an elevated platform, not shaded by a building or trees and was oriented in a direction that made the capture of the incident solar radiation more efficient (Figure 5.1).

Figure 5.1: Pictorial view of the solar tunnel dryer from the collector end.

Half of the dryer consisted of a flat-plate collector for heating the incoming air and the other half, a tunnel drying chamber, where the product being dried was placed. Plain metal sheets with wooden frames were used at base of the collector and drying chamber in several small sections which were joined together in series. At the bottom of the dryer in between the two metal sheets, an insulation material (glass wool) was used to reduce loss of heat from both the collector and drying chamber. One photovoltaic solar module provided the power to run the two direct-current fans (connected in series), which provided the required airflow within the tunnel dryer. Black paint was used at the collector base to facilitate absorption of solar radiation.

A UV stabilized plastic sheet, was fixed as a sloping roof cover over the collector and the drying chamber to provide greenhouse effect as well as to protect the product from insects and rain. A metal tube was fixed to one end of the plastic sheet, which allowed loading and unloading of the dryer by rolling of the plastic sheet up and down. The operation of the dryer is such that solar radiation gets to the absorber surface by passing through the transparent cover of the collector, providing heat energy which is transferred to the air. From the collector, the heated air then moves to the drying chamber, transfers heat and absorbs moisture from the products thus causing dehydration. Products within the drying chamber are also heated by direct solar radiation passing through the transparent cover.

5.2.2. Experimental procedure

Experimental drying runs were conducted under the climatic conditions of Isiolo county in the months of August and September, 2017. The weather was generally sunny during the drying processes. For all drying experiments, fresh beef of about 5.0 mm thickness were weighed and spread as a single layer on trays (layered with plastic nets) which were loaded into the drying chamber. Each experiment was started at 9:00 a.m (after completion of loading) and discontinued at 4:00 p.m. The drying section of the tunnel dryer was divided into four sub-sections in order to evaluate drying kinetics of beef at different areas of the dryer. Control samples of beef were placed on a raised platform beside the drier and spread out as a single layer, allowing air to pass from beneath the tray. This was done to compare the solar tunnel dryer performance with dehydration in the open sun. At the beginning of drying, moisture loss from the samples was determined by weighing samples from one point of each tray (from each sub-section of the drying chamber) after every 30 min and during the last stage of the process, after every 1 h, using a digital electronic balance (ESA 600, Salter Brecknell, UK: accuracy ±0.01g) placed outside the tunnel dryer. At 4:00 pm, the beef slices were collected and placed in a room at ambient conditions, then loaded again the next morning to continue with the drying process. The drying process occurred simultaneously for both the experimental and control samples under the same weather conditions and this was done in duplicates.

During the drying process, ambient and drying air temperatures and relative humidity, air velocity at collector inlet and solar radiation intensity were measured. Relative humidity and temperature sensors were placed within and outside the tunnel dryer to measure and relative humidity and temperature respectively and data collected by data logger units connected to the sensors. The sensors were inserted at the inlet of the four sub-sections (A, B, C and D) of the drying compartment from the collector end to the end of the drying chamber of the tunnel dryer respectively. The points of insertion of the probes were labeled (1 to 5) from the beginning of sub-section A to the end of subsection D respectively. An anemometer (Model Taylor 3132, Taylor Instruments, Toronto, Canada: accuracy ±0.01m/s) was used to measure drying air velocity after every one hour. A pyranometer, placed on a raised horizontal surface outside the dryer and connected to a data logger unit was used for solar radiation intensity measurement. The temperature, relative humidity and pyranometer data logger units recorded data after every five seconds. The drying process was completed on the second day after a total drying time of 11 h for all the samples. Approximately 20 kg of fresh beef slices were dried to approximately 7.5 kg of dried beef samples after. They were then cooled and sealed in plastic bags.

5.2.3. Analysis of drying data

5.2.3.1. Experimental drying curves

Calculation of moisture content was done as shown below:

$$M_t = \frac{(W_0 - W) - W_1}{W_1} \tag{5.1}$$

where M_t is the moisture content (% dwb) at time t, W_0 is initial sample weight (g), W is the amount of evaporated moisture (g), and W_1 is dry matter content of sample (g).

Drying curves were presented in terms of moisture content vs drying time and drying rate vs moisture content graphs. The drying rate (DR) of beef slices was calculated using the following equation:

$$DR = \frac{M_t - M_{t+\Delta t}}{\Delta t} \tag{5.2}$$

where $M_{t+\Delta t}$ is the moisture content at time ‘t+Δt’ (% dwb) and t is time (min).

5.2.3.2. Mathematical modelling

Fick’s diffusion equation for solid materials with slab geometry was applied to the beef drying experimental data as presented below.

$$MR = \frac{M_t - M_e}{M_0 - M_e} \tag{5.3}$$

where MR is the moisture ratio, M_e is equilibrium moisture content (% dwb), M_t is moisture content at any time (% dwb) and M_0 is the initial moisture content (% dwb).

However, owing to the continuous relative humidity fluctuations of drying air during the process of solar drying, determination of M_e becomes a challenge (Sacilik *et al.*, 2005). The equation can therefore be reduced to

$$MR = \frac{M_t}{M_0} \tag{5.4}$$

The drying data were analyzed in terms of moisture ratio vs drying time graphs. Fitting of the experimental data obtained was done by application of five semi-theoretical models presented in Table 5.1.

Table 5.1: Mathematical models used for the solar drying curves

Model	Equation	References
Newton	$MR = \exp(-kt)$	(Fudholi et al., 2011)
Logarithmic	$MR = a\exp(-kt) + c$	(Chandra and Singh,1995)
Page	$MR = exp(-kt^n)$	(Page, 1949; Doymaz, 2004)
Henderson and Pabis	$MR = a\exp(-kt)$	(Henderson and Pabis, 1961)
Two-term exponential	$MR = aexp(-kt) + (1-a)exp(-kat)$	(Sharaf-Eldeen *et al.*, 1980)

where t is time (min), k is the drying rate constant (min^{-1}) and a, n and c are drying constants.

The drying rate constants and coefficients of drying models were estimated using a non-linear regression procedure using the iterative non-linear least square fitting method of Excel 2008 software. The statistical validity of the models were assessed and compared by using the coefficient of determination (R^2), reduced chi-square (χ^2), root mean square error (E_{RMS}) and mean relative percent error (P). The parameters were calculated as follows: (Equations 5.10-5.13).

$$R^2 = 1 - \left(\frac{\sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})^2}{\sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})^2}\right) \tag{5.10}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})^2}{\mathrm{N} - \mathrm{z}} \tag{5.11}$$

$$E_{RMS} = \left(\frac{1}{N}\sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})^2\right)^{\frac{1}{2}} \tag{5.12}$$

$$P = \frac{100}{N}\sum_{i=1}^{N}\frac{|MR_{exp,i} - MR_{pre,i}|}{MR_{exp,i}} \tag{5.13}$$

where $MR_{exp,i}$ is the ith experimental moisture ratio, $MR_{pre,i}$ is the predicted dimensionless moisture ratio, $MR_{exp,avg}$ is the average experimental moisture ratio, N is the number of observations and z is the number of constants.

R^2 was used as the primary comparison criteria for determining the goodness of fit of the models to the curves. A higher R^2 value and lower values of χ^2, E_{RMS} and P for the models were considered to have better fits.

5.2.4. Effective moisture diffusivity determination

The effective moisture diffusivity of the samples was estimated by using the simplified Fick's second diffusion model. The solution of Fick's second law, with the assumption of moisture migration by diffusion, constant diffusion coefficient and temperature, negligible shrinkage and infinite slab geometry as given by Crank, (1975) was used and effective moisture diffusivity obtained by plotting experimental drying data in terms of ln (MR) versus time (s). After determining the slope of the straight line, D_{eff} was calculated using the following equation: (Akpinar, 2006)

$$D_{eff} = \frac{-slope\ 4L^2}{\pi^2} \tag{5.14}$$

5.3. RESULTS AND DISCUSSION

5.3.1. Parameters of drying air

The ambient temperature and solar radiation intensity during the drying period (August-September, 2017) varied from a minimum of 21.3 °C to a maximum of 38.9 °C and from 476.3 to 1000 W/m^2 respectively. The ambient relative humidity ranged from 48 to 69.5% whereas the average air velocity at the air inlet of the solar tunnel dryer varied from 0.02 to 0.18 m/s. Variations of the ambient air temperature and solar radiation intensity for a typical day during solar drying of beef samples in August, 2017 is shown in Figure 5.3. The ambient air temperature and solar radiation reached their highest values at around 12:00 noon.

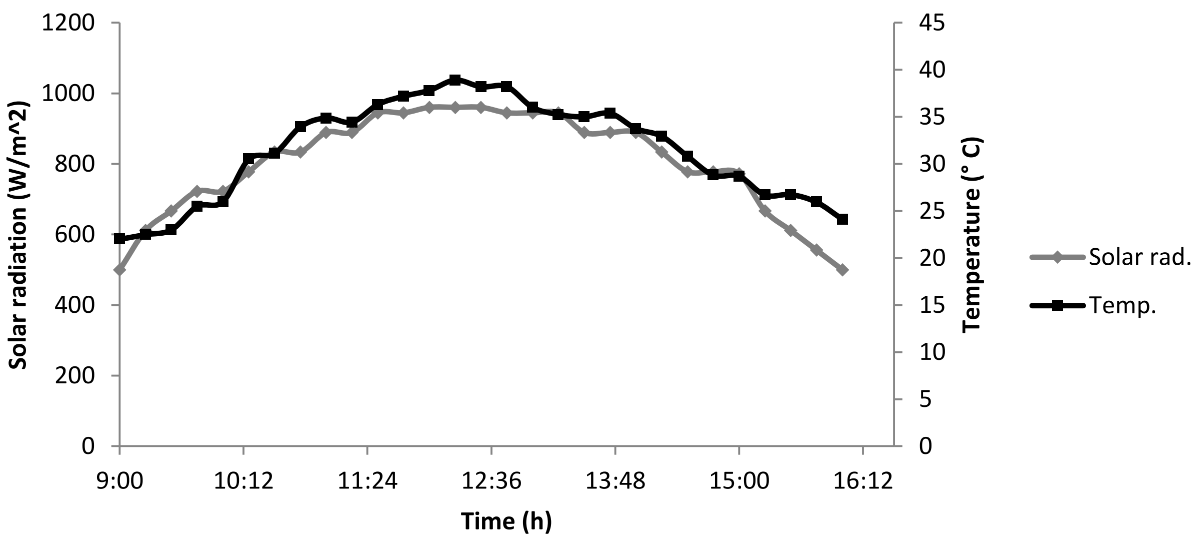

Figure 5.2: Variation of the ambient air temperature and solar radiation intensity for a typical day during solar drying of beef samples.

The drying temperature at any time in solar tunnel dryer was greater than the ambient temperature, whereas the relative humidity in the tunnel was lower than the ambient relative humidity.

Figure 5.4 shows the variations of the ambient temperature and relative humidity at the collector outlet with the time of day during solar drying for a typical day of September 2017. The drying temperature and relative humidity at this point in solar tunnel dryer varied continuously from morning to evening. The temperature and relative humidity of drying air ranged from 36.1 to 60.1 °C and 16.5 to 28.3 % respectively. A close relationship between temperature and humidity was observed where relative humidity was high at low temperatures and vice-versa.

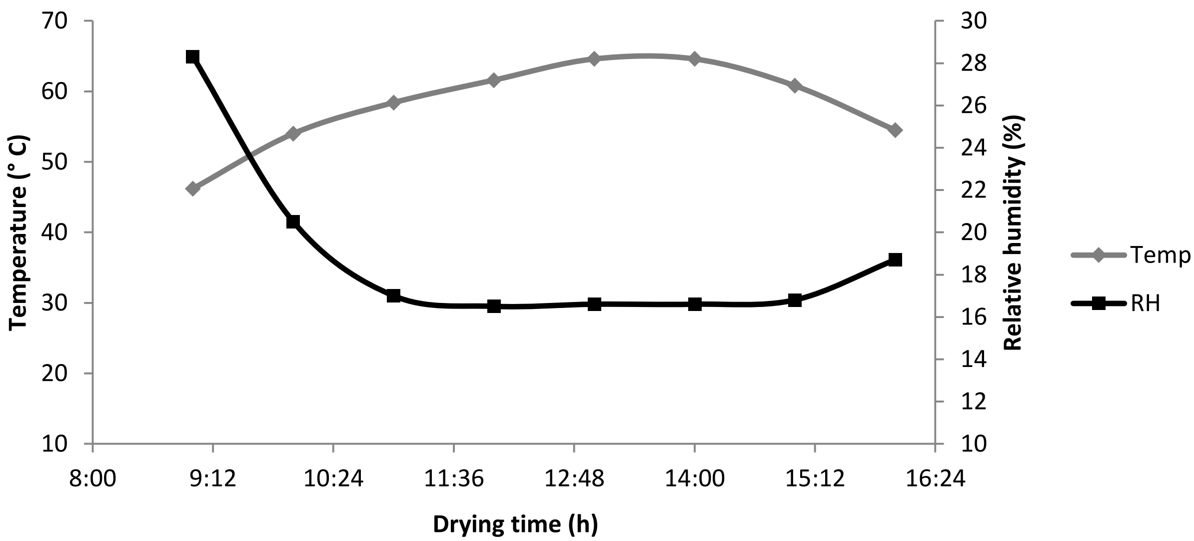

Figure 5.3: Variation of the ambient temperature and relative humidity at the collector outlet with time of day during drying in a solar tunnel dryer.

The temperature variations at different points (1-5) inside the drying chamber at different times during a typical day of drying in the solar tunnel dryer are presented in Figure 5.5.

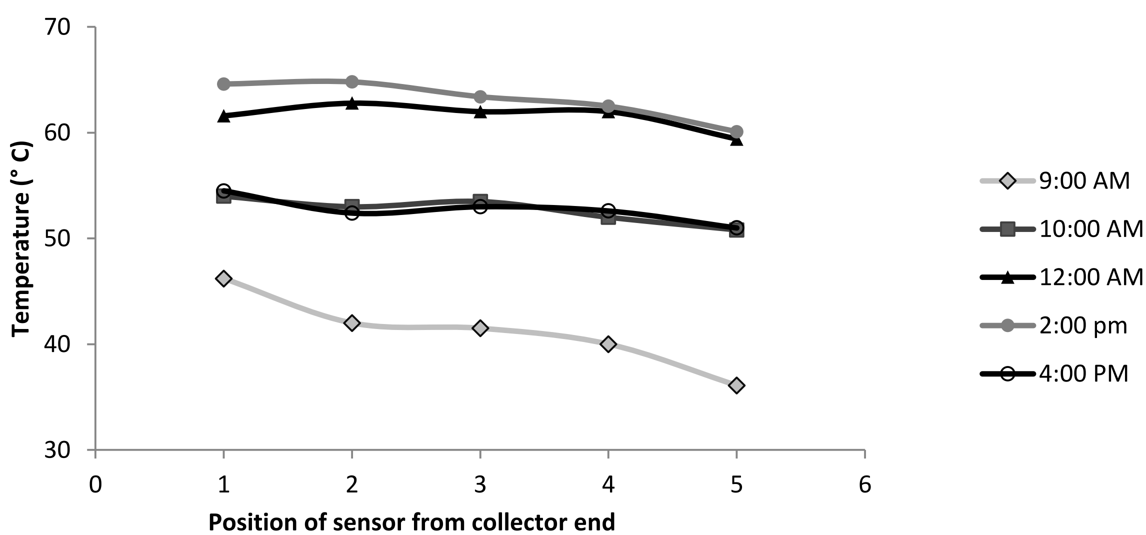

Figure 5.4: Variation of temperature with time at different points (1-5) in the drying chamber for a typical day of drying in a solar tunnel dryer.

The temperatures inside the solar tunnel dryer ranged from 42.6 to 64.6, 42 to 64.8, 41.5 to 63.4, 40 to 62.5 and 36.1 to 60.1 °C from the collector end to the end of the drying chamber respectively. The highest temperature (64.8 °C) was recorded at 14:00 hours at the collector end of the dryer while the lowest temperature (36.1 °C) was recorded at 9:00 hours at the end of the drying chamber. The temperatures were observed to be highest between 12:00 am and 2:00 pm. During this period, there was minimum variation in drying temperatures within the drying chamber. This could be attributed to regulation by the air flow rate in the dryer. During the high insolation period, more energy is received by the collector which is intended to increase the drying air temperature. However, this is compensated by the increase of the air flow rate due to more solar energy received by the PV solar module, providing more driving power to the fans (Bala *et al.,* 2003).

Air temperature decreased along the length of the dryer during the first day of drying and this decrease was more pronounced during the early phase of drying (9:00 am, Figure 5.5). During this phase, when the moisture content of the product is still high, heated air from the collector section provides the latent heat of vapourization and also mixes with moisture from the material and is continuously cooled as it passes through the dryer section towards the outlet of the tunnel dryer. Similar results were reported by Shirmer *et al.* (1995) and Hossain and Bala (2007) who found that that temperature profile along the dryer depended not only on the solar radiation but also on the moisture content of bananas and hot chilli being dried in a solar tunnel dryer respectively.

5.3.2. Experimental drying curves

Figure 5.6 shows the moisture content of beef as a function of drying time during open sun drying and solar drying in different sections of the drying chamber for a typical experimental run. The moisture content decreased considerably with increasing drying time. The moisture content of beef decreased from 309.39 % to between 2.32 and 9.56 % (dry weight basis/dwb) after 11 h of drying in the different sections of the solar tunnel drier (A-D) while it took the same time to bring down the moisture content in a similar sample to 24.76 % (dwb) with traditional sun drying method. This showed that open sun drying process required a longer time to reduce the moisture content of beef to the same level as samples dried in the solar tunnel dryer.

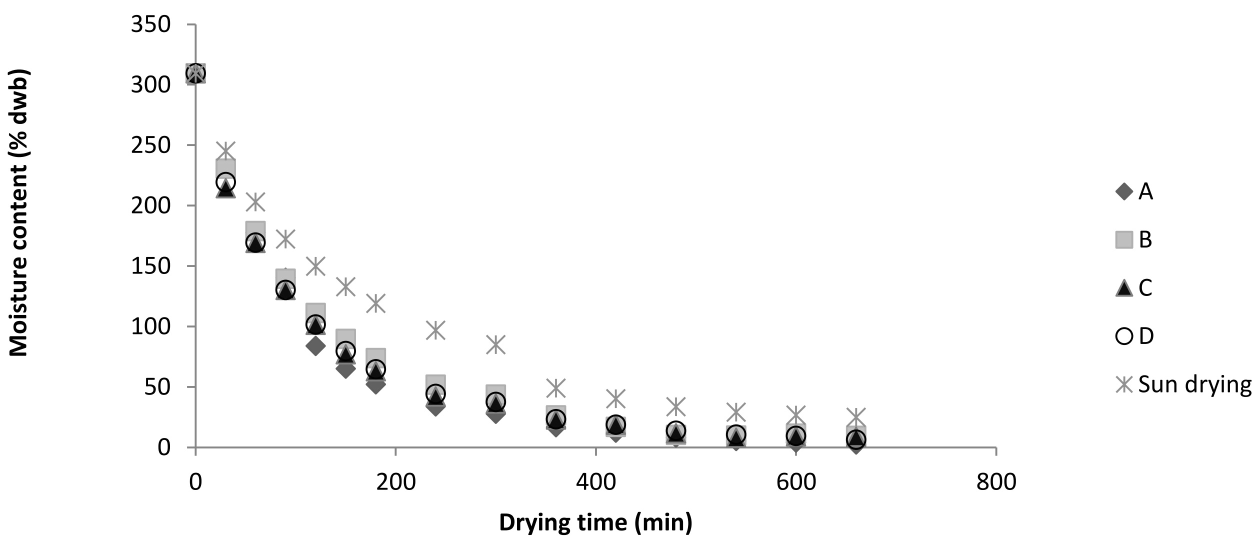

Figure 5.5: Moisture content vs drying time graph for a typical experimental run during beef drying at different sections of the solar tunnel dryer (A-D) compared to open sun drying.

The beef inside the tunnel dryer lost moisture faster because it received energy from incident solar radiation as well as more energy transported from the collector by forced convection. The control samples on the other hand, received energy from incident solar radiation and less energy transported from surrounding environment by natural convection. Moreover, a significant amount of heat energy was also lost to the environment (Hossain and Bala, 2006). This caused the temperature in the dryer to be higher than the ambient temperature and the corresponding relative humidity to be lower than the ambient relative humidity so that the moisture carrying capacity of the air was increased. Generally, the moisture absorption capacity of air is affected by the absolute humidity of the air entering the collector as well as the temperature to which it is subsequently heated.

A typical graph representing the drying rate versus moisture content during solar tunnel drying (section B) and sun drying of beef is shown in Figure 5.7. Drying rate of beef in the solar tunnel dryer was higher than for sun dried beef samples.

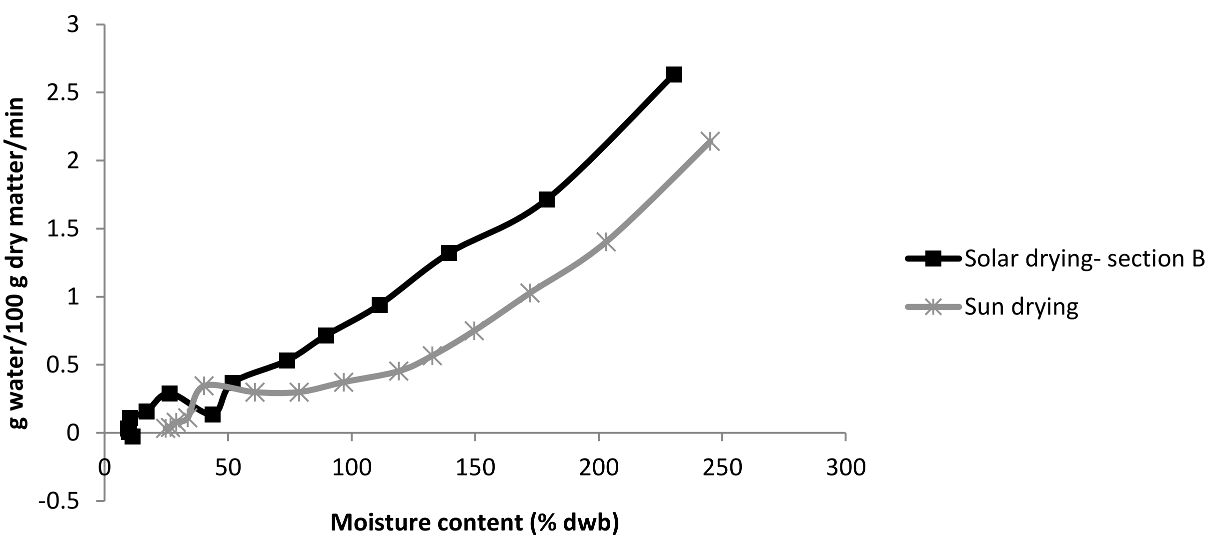

Figure 5.6: Drying rate vs moisture content graph during solar and sun drying of beef.

Drying occurred predominantly in the falling rate period in both the solar tunnel dryer and during open sun drying. During this period, drying rate is controlled predominantly by diffusion of moisture from the interior of food material to its surface and it decreases continuously with decreased moisture content and increased drying time (Sacilik *et al.*, 2005). This can be attributed to the diminishing presence of water in its free form as the moisture-food interactions become stronger (Shivhare *et al.*, 2004). These results were in agreement with those of Sacilik *et al.* (2005) for drying tomatoes in a solar tunnel dryer.

5.3.3. Mathematical modelling

Tables 5.2 and 5.3 show the drying coefficients and evaluation criteria used to compare the statistical validity of fits of the five drying models to the experimental data for beef dried closest to the outlet of the drying tunnel (Section D) and by open sun drying respectively.

Table 5.2: Estimated parameters and comparison criteria of moisture ratio for solar dried beef samples

Model	Model constants		R^2	E_{RMS}	P	χ^2
Newton	k	0.009056	0.995733	0.030503	32.2638	0.000997
Page	n	0.802121				
	k	0.023376	0.998872	0.00984	8.291977	0.000112
Logarithmic	a	0.87343				
	c	0.032329				
	k	0.008816	0.9948529	0.009348	4.221706	0.000109
Henderson and	a	0.956391				
Pabis	k	0.008578	0.993716	0.027484	29.44735	0.000872
Two-term	a	0.284285				
exponential	k	0.023655	0.998815	0.013127	16.54509	0.000199

where R^2, E_{RMS}, P and χ^2 are coefficient of determination, root mean square error, mean relative percent error and reduced chi-square respectively.

All models gave a good fit to the solar drying experimental data with the values of R^2 greater than 0.99 (Table 5.2) whereas for sun drying, only the page and two-term exponential models had R^2 values greater than 0.99 (Table 5.3).

Table 5.3: Estimated parameters and comparison criteria of moisture ratio for sun dried beef

Model	Model constants		R^2	E_{RMS}	P	χ^2
Newton	k	0.00531	0.989623	0.04373	13.20134	0.002049

Page	n	0.782733				
	k	0.016745	0.996547	0.016153	0.874373	0.000301
Logarithmic	a	0.843103				
	c	0.046292				
	k	0.00514	0.9886215	0.018022	0.019305	0.000406
Henderson and	a	0.925318				
Pabis	k	0.004785	0.985747	0.034661	8.915734	0.001386
Two-term	a	0.196418				
exponential	k	0.021334	0.996096	0.020104	4.110848	0.000466

where R^2, E_{RMS}, P and χ^2 are coefficient of determination, root mean square error, mean relative percent error and reduced chi-square respectively.

For the two drying methods, page model gave the highest R^2 values followed by the two-term exponential model. The values for P obtained for the Page and logarithmic models for both drying methods were less than 10 %, which is in the acceptable range. These models also gave the lowest values of E_{RMS} and χ^2 compared to the other models. Therefore, the Page model was considered the best model in the present study to represent the solar tunnel and sun drying behaviour of beef. However, the fitting quality of the models to the experimental data was better for solar tunnel drying than for open sun drying. As expected, the drying rates represented by k values for all the thin layer drying models (Tables 5.2 and 5.3), were higher at the drying chamber of the solar tunnel dryer compared to open sun drying.

Figure 5.8 represents the comparison between experimental and predicted values of moisture ratio with drying time using the Page model for sun and solar dried beef samples at different dryer sections.

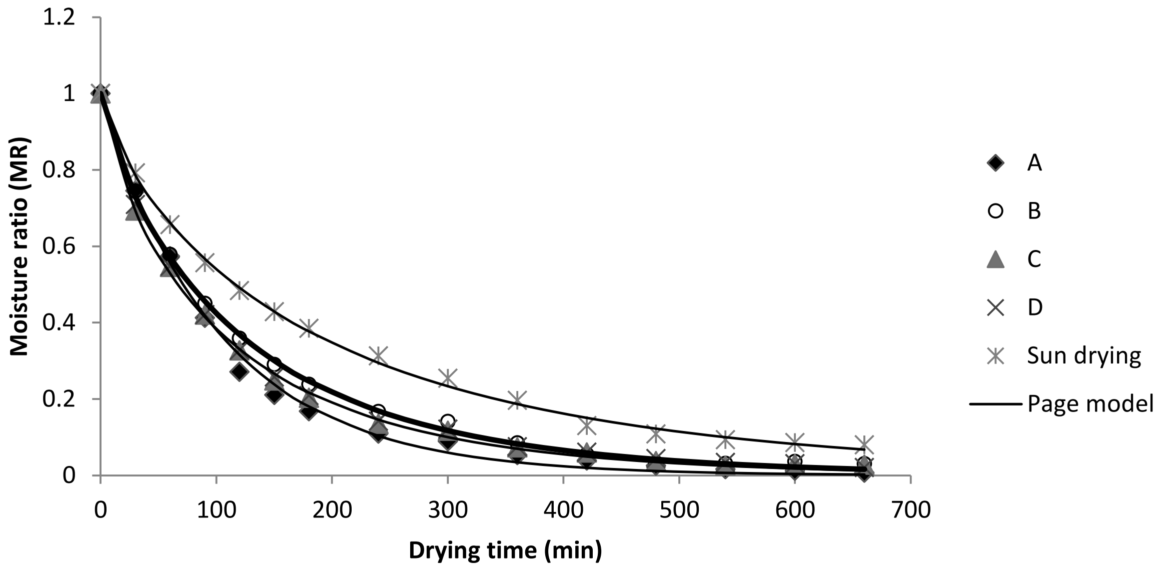

Figure 5. 7: Variation of predicted and observed moisture ratios against drying time using page model for beef dried at different drier sections (A-D) and in the open sun.

It can be seen from the curves that there was a good agreement between experimental and predicted moisture ratios. This indicates the suitability of the Page model in describing the drying behaviour of beef. The suitability of the page model for describing the solar tunnel drying behaviour of other foods has also been established by Elicin and Sacilik (2005).

5.3.4. Effective moisture diffusivity

Effective moisture diffusivity values were calculated by using Equation 5.16; from the slopes of straight lines generated from plots of experimental drying data ln (MR) vs drying time (Figure 5.9).

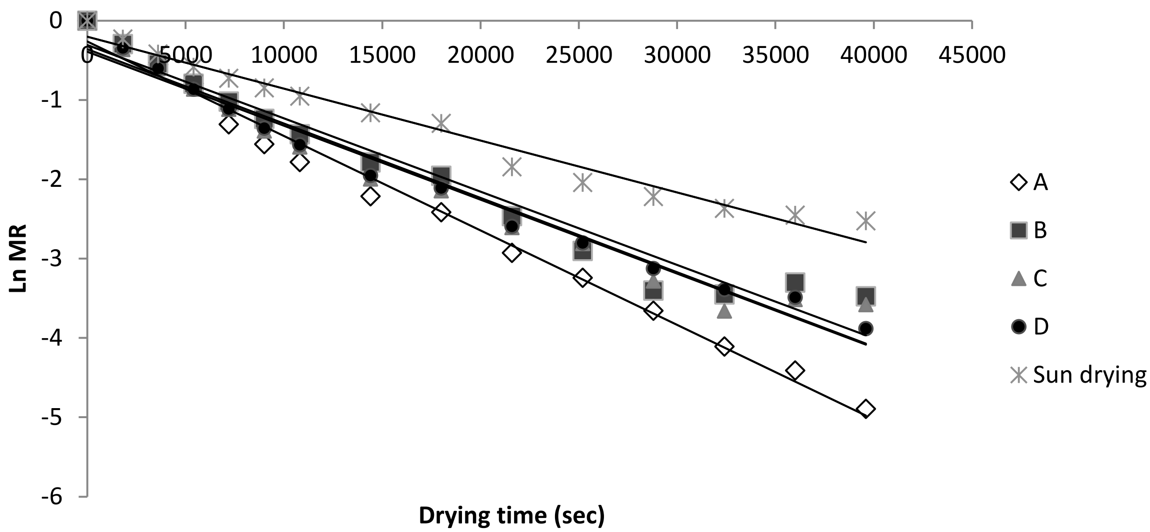

Figure 5.8: Linear relationship between logarithmic moisture ratio (ln MR) and drying time at for beef dried at different dryer sections (A-D) and for sun dried beef.

The values of D_{eff} for different dying methods are presented in Table 5.4. The effective diffusivity (m^2/s) for solar dried beef was 2.536 $x10^{-10}$ at the dryer section closest to the collector outlet (section A) and a constant value of 2.282 $x10^{-10}$ for beef dried in the subsequent sections (sections B, C and D). The D_{eff} value for samples dried in the open sun was 1.775 $x10^{-10}$. Section A of the drying chamber in the tunnel dryer generally exhibited on average a higher temperature of drying air during the solar drying process (Figure 5.5), resulting in higher activity of water molecules in the product (Shi *et al.*, 2008) and thus a higher D_{eff} value. The values of D_{eff} for beef samples in the solar tunnel dryer were generally higher than for open sun drying.

Table 5.4: Effective moisture diffusivity values for beef dried using different methods

Drying method	Dryer sections	(D_{eff} x 10^{10} m^2/s)
Solar tunnel drying	A	2.536
	B	2.282
	C	2.282
	D	2.282
Open sun drying		1.775

where D_{eff} is effective moisture diffusivity

The values of effective diffusivity were within the standard range for food products (10^{-9} – 10^{-11} m^2/s; Zogzas et al., 1996) and could be compared to the reported values of $1.31x10^{-9}$ to $1.07x10^{-9}$ m^2/s for organic tomato (Sacilik et al., 2006) and $1.66x10^{-11}$ to $1.94x10^{-11}$ m^2/s for pumpkin (Sacilik, 2007) during sun and solar tunnel drying of the food products.

5.4. CONCLUSIONS

A solar tunnel dryer (Hohenheim type) can be used for effective drying of beef under the climatic conditions of Isiolo county in Kenya. The moisture content can be reduced to between 2.32 and 9.56 % (dwb) in 11 hours of drying in the solar tunnel compared 24.76 % (dwb) in a similar sample with traditional sun drying method. All drying processes of beef occur in the falling rate period. The Page model adequately describes the solar drying behaviour of beef in a solar tunnel dryer. The Effective moisture diffusivity values for solar tunnel dried beef samples vary from 2.282 to 2.536 x 10^{-10} m^2/s and is lower for samples dried in the open sun.

CHAPTER 6: QUALITY CHARACTERISTICS OF BEEF DRIED IN A SOLAR TUNNEL DRYER UNDER DIFFERENT STORAGE CONDITIONS

ABSTRACT

Many deteriorative changes occur in meat during preparation, drying and storage, which affect the quality characteristics of the dried product. The aim of this study was to determine the effect of solar tunnel drying, packaging type and storage time on the quality characteristics of dried beef. The beef samples were dried in different sections of the solar tunnel dryer and in the open sun as a control. The physico-chemical and sensory quality attributes of the dried products were evaluated using standard procedures. The effect of packaging type (glass, paper, polyethylene and aluminium foil) and storage time on the chemical and microbial quality of dried beef was also determined.

There was a significant decrease in L*, a* b* and C* colour parameters and an increase in H*colour parameter after sun and solar drying of beef samples. The moisture content and rehydration ratios of solar dried beef varied from 2.31±0.23 to 8.73±0.16 % and 1.24±0.03 to 1.28±0.05 respectively while for sun dried samples, these parameters were 19.85±0.44 % and 1.20±0.05 respectively. The adhesiveness of samples closest to the collector end of the dryer was significantly lower ($p \leq 0.05$) whereas hardness (N), firmness (N), springiness (%) and resilience were higher compared to sun dried beef samples. Solar dried beef scored higher than the sun dried samples for all the sensory parameters evaluated whereas dried and cooked samples scored significantly higher ($p \leq 0.05$) than their uncooked counterparts for both drying methods. Solar dried beef samples close to the center of the drying chamber (sample C, with between 7.02±0.08 and 9.64±0.06 % moisture content) were the most stable to moisture changes during storage.

There was a gradual increase in PV of all the dried samples during storage in all the packaging systems. The total viable count (TVC), *Staphylococcus aureus* and yeasts and moulds were significantly higher for the sun dried samples compared to solar dried beef. The changes in moisture content, TVC and PV in dried beef samples stored in glass jars or aluminium foil wraps were significantly lower ($p \leq 0.05$) compared to polyethylene and paper packaged samples.

6.1. INTRODUCTION

The quality of dehydrated foods depends not only on the initial quality of the raw material but also on the changes occurring during processing and storage. When meat has undergone intensive drying, the primary structures of the product can change substantially, affecting its quality. Due to the low moisture content of the dried meat products, they are normally termed as shelf-stable and can therefore be stored under ambient environmental conditions. For this type of food product, refrigeration is not required during distribution and storage (Lawless and Heymann, 2010). However, all foods continue to undergo modifications in structure, composition and properties during storage before consumption. The breakdown of a food product during transportation and storage is influenced by factors such as nature of the product, packaging material and intrinsic and extrinsic environmental conditions to which the food product is exposed. These play a significant role in determining the spoilage mechanisms for different types of foods (Lawless and Heymann, 2010). The spoilage mechanisms can either be physico-chemical in origin or due to the action of microbiological factors, which can all lead to changes in the sensory quality of the product (Valero *et al*., 2013).

Of the categories of spoilage that can occur, the two principal spoilage mechanisms that affect shelf-life of dried meat products are microbial growth and oxidation of myoglobin (browning) or lipids (rancidity). Shelf life testing is carried out by holding representative samples of the final product under conditions likely to mimic those that the product will encounter from processing to consumption (Swain *et al.,* 2013). The traditional approach consists of setting a cut-off point along the storage period at the time when any of the measured attributes exceeds a pre-established limit. This can be done by using real time shelf-life testing under typical storage conditions or accelerated shelf-life testing, where the product is stored under accelerated conditions (i.e. elevated temperatures) that increase the rate of degradation occurring in the product. The latter method is generally useful for products with a long shelf-life.

Many studies have been reported on the effect of different drying methods on the quality of dried meat products including beef (Rahman *et al.,* 2005; Lim *et al.,* 2012; Apata *et al*., 2012; Adeyeye, 2016). As much as solar tunnel drying of food products is gaining a lot of interest as an elaboration of sun drying and an efficient system of utilizing solar energy (Bala and Janjai, 2012), most of the studies on dried product quality after solar tunnel drying have focused on fruits and vegetables (Shirmer *et al.,* 1995; Bala *et al*., 2003; Sacilik *et al.,* 2006; Hossain and Bala, 2007). Research on quality of dried beef after solar tunnel drying is limited. This paper therefore, studied effect of sun and solar tunnel drying on the physico-chemical (in terms of colour, moisture content, rehydration ratio, and texture) and sensory quality of dried beef.

On the other hand, different studies have been reported on the effect of packaging methods on quality characteristics of different meat products, with the majority focused on modifying food atmospheric conditions (Jo *et al.,* 1999; Ahn *et al*., 2000; Montgomery *et al.,* 2003; Yilmaz and Demirci, 2010; Limbo *et al.,* 2010; Maria Gomez and Lorenzo, 2012; Amaral *et al.,* 2015). However, research on the best packaging material for storage of dried beef with the aim of minimal reduction of essential quality parameters is not apparently available in literature. The present study also focused on the effect of storage time and packaging type during accelerated storage, on the moisture content, peroxide value and microbiological quality of dried beef samples

6.2. MATERIALS AND METHODS

6.2.1. Sample collection and preparation

Meat (hind leg beef) with a moisture content of 76.69%.was sourced from a local butchery in Isiolo county, Kenya and stored in a freezer overnight to have enough consistency for cutting. The beef was deboned after fat removal then sliced into approximately 5.0 mm thick strips with a mechanical slicer (Bizerba GmbH & Co.Kg., Balingen, Germany).

6. 2.2. Drying equipment and drying methods

A Hohenheim type solar tunnel drier (as described by Bala and Dephnath, 2012), installed at Ewaso Ng'iro North Development Authority (ENNDA) premises, Isiolo county, Kenya was used to dry beef samples. The dryer was divided into four sub-sections and the samples within each section named A, B, C and D from the collector end to the end of the drying chamber of the tunnel dryer respectively in order to determine the effect of sample position on the quality of the dried product. The samples were spread as a single layer on trays (layered with plastic nets) which were loaded into the different sections of the drying chamber. Each experiment was started after completion of loading (at 9:00 a.m) and discontinued at 4:00 p.m on the first day.

To compare the performance of the solar tunnel dryer with that of open sun drying, control samples of beef were spread out in a tray as a single layer and placed on a raised platform beside the drier allowing air to pass from beneath the tray. Both experimental and control samples were dried simultaneously under the same weather conditions. During the drying period, the ambient temperature, ambient relative humidity, inlet air velocity and solar radiation intensity values were; 21.3-38.9 °C, 48-69.5%, 0.02-0.18 m/s and 476.3-1000 W/m^2 respectively. Temperature profile along the tunnel dryer varied from 42.6 to 64.6, 42 to 64.8, 41.5 to 63.4, 40 to 62.5 and 36.1 to 60.1 °C at the inlet of section with samples A to the outlet of section with samples D of the solar tunnel drier respectively. The dehydration processes were done in duplicates and completed on the second day after a total drying time of 11 h for all the drying methods. The dried beef samples were collected, cooled in a room to the ambient temperature and packaged in low density polyethylene bags for quality evaluation.

6.2.3. Effect of drying methods on physico-chemical and sensory quality characteristics of dried beef

6.2.3.1. Color measurement

Color measurements for sun and solar dried beef samples were performed using a hand held tri-stimulus colorimeter (Minolta Chroma Meter CR-200, Minolta Co., Osaka, Japan). The L*, a*and b* colour coordinates, were determined according to the ISO/CIE standard color space system proposed by Commission Internationale de l'Eclairage (Joint ISO/CIE Standard, 2008).

where: L* is the lightness or darkness (black, L*=0; white, L*=100), +a* is the redness, -a* is the greenness, +b* is yellowness, and -b* is the blueness (Soysal, 2004). In addition the hue-angle (h°) and the saturation index or chroma (C*) which describe the hue colour and brightness or vividness of color, respectively, were calculated using Equations 6.1 and 6.2 according to AMSA (2012) guidelines:

$$h^0 = \tan^{-1}(\frac{b^*}{a^*}) \tag{6.1}$$

$$\mathrm{C} *= (a^{*2}+b^{*2})^{0.5} \tag{6.2}$$

6.2.3.2. Moisture content

The moisture content of the dried samples was measured at a fixed temperature of 105 °C using method 967.08 (AOAC, 2005)

6.2.3.3. Rehydration ratio

To account for the ability of the sun and solar dried beef samples to absorb water and return to its original form, rehydration ratio was determined. The dried sample was weighed, immersed in a hot water bath at 100 °C for 10 min, drained and reweighed. Excess water was removed using a filter paper and rehydration ratio calculated as shown in Equation 6.3 (Doymaz, 2014). The procedure was conducted in triplicate for each sample.

$$RR = \frac{M}{M_0} \tag{6.3}$$

where *RR* is the rehydration ratio, and *M* and M_0 are the sample weights after and before placing in the hot water bath, respectively.

6.2.3.4. Instrumental texture

Due to the irregular structure of dried meat products and variability in meat texture analysis methods (Salakova, 2012), three texture measuring instruments were used to evaluate the firmness, hardness and other texture parameters of solar and sun dried beef samples.

Volodkevich bite jaws firmness

Texture (firmness) measurements for the dried beef samples were done using a TA.XT.plus Texture Analyzer (Stable Microsystems, Surrey, United Kingdom) with the volodkevich bite jaws (HDP/VB*) fixture. The volodkevich test was carried out using a volodkevich bite jaws cell at a deformation rate of 100mm/min. The pre-test speed, test speed, post-test speed, trigger force and the compression distance were set at 5.0 mm/s, 5.0 mm/s 2.0 mm/s, 5g and 25% respectively. A 50 kg load cell was used to compress the samples. Pieces of dried beef measuring 1 cm^2 (square cross-section), were placed parallel to the compression plate surface and compressed as shown in Figure 6.1.

Figure 6.1: Front view of TA.XT.*plus* Texture Analyser showing the position of the sample between the upper and lower jaws of the volodkevich bite jaws cell.

Rheometer puncture test

To measure hardness of dried beef, puncture test was done using a Rheometer (Sun Rheometer Compaq-100, Sun Scientific co. ltd, Japan) equipped with a cylindrical probe with a diameter of 5 mm as shown in Figure 6.2. Samples were punctured at a distance of 3 mm with a test speed of 500 mm/min and a load cell of 10 kg.

Figure 6.2: Front view of a rheometer equipped with a cylindrical probe after instrumental setting.

Texture profile analysis

Texture Profile Analysis (TPA) of rehydrated beef samples was done using a TA.XT.*plus* Texture Analyzer (Stable Microsystems, Surrey, United Kingdom), equipped with a 50 kg load cell.

Figure 6.3: Front view of the Texture Analyser showing the mechanism of compression.

Texture profiling involved compressing the test substance at least twice and quantifying the mechanical texture parameters from the recorded force-deformation curves (Szczesniak, 2002). These included; hardness (N), cohesiveness, adhesiveness, springiness (%), chewiness (N) and resilience. Figure 6.3 shows the mechanism of action of the TA.XT.*plus* Texture Analyser. The instrument settings were: pre-test speed 1.0 mm/s; test speed 5.0 mm/s; post-test speed 5.0 mm/s; 30% compression, trigger type auto force 5 g; data acquisition rate 200 pps, 38 mm diameter acrylic cylinder probe. The waiting time between the first and second compression cycle was 5 s.

6.2.3.5. Sensory evaluation

The dried beef samples were cooked separately at 100 °C for 20 min and cut into pieces of sizes 2cm x 2cm x thickness. The cooked and uncooked samples were labelled with random 3-digit codes and presented randomly to panellists consisting of 15 volunteers who had been selected and trained. Uncooked samples of dried beef were observed for their colour, odour, appearance and overall acceptability whereas cooked samples of dried beef were evaluated and compared with uncooked control samples for their colour, odour, flavour, texture, appearance and overall acceptability. The beef samples were placed into white saucers and sensory attributes tested on a nine point hedonic scale, where 1= dislike extremely, 2 = dislike very much, 3 = dislike moderately, 4 = dislike slightly, 5 = neither like nor dislike, 6 = like slightly, 7 = like moderately, 8 = like very much and 9 = like extremely (Wichchukit and O'Mahony, 2015).

6.2.4. Effect of packaging type and storage time on the chemical and microbial quality characteristics of dried beef

6.2.4.1. Storage studies

Solar and sun dried samples were packaged in hermetically sealed low density polyethylene (LDPE) pouches of gauge 150 microns, aluminium foil (wrapped carefully to prevent tearing), glass jars with sealing lids and greaseproof brown paper bags (with openings folded and taped securely after expelling as much air as possible). These were then stored in a hot air oven at elevated temperatures (55 °C) for five days to simulate product shelf life at typical storage conditions (ambient temperature). This process is based on Q_{10} approach for shelf life estimation. The Q_{10} value can be defined as the temperature quotient for a 10 °C rise in temperature (Equation 6.4).

$$Q_{10} = \frac{shelf\ life\ at\ T_1}{shelf\ life\ at\ T_1 + 10\ °\mathrm{C}} \tag{6.4}$$

where T_1 is the typical storage temperature.

According to FAO, (1995) the shelf life of dried beef with a water activity less than 0.6 is approximately 1 year. Given the basic assumption that the Q_{10} value of most foods is 2, storage at 55 °C for one day at an ambient temperature of 22 °C would give accelerated shelf life duration of 37.06 days. Quality parameters such as moisture content, peroxide value and microbial counts were measured before storage and assessed on a daily basis during the storage period.

6.2.4.2. Moisture content

Moisture content during storage was determined as described in section 6.2.3.2.

6.2.4.3. Peroxide value

Oxidative stability of dried beef samples was measured using titrimetric determination of the amount of peroxide or hydroperoxide groups, the initial product of lipid oxidation. To 5g of sample, 30 ml glacial acetic acid chloroform solution (3:2 v/v) was added and swirled. Excess potassium iodide (0.5 ml of KI solution) was added to react with the peroxides and iodine liberated. After 1 min, 30 ml of H_2O was added and the solution titrated using 0.1 N sodium thiosulfate ($Na_2S_2O_3$) with 0.5ml of 1% starch used as indicator. Titration was continued until blue colour disappeared. The peroxide value (milliequivalent peroxide/kg sample) was calculated using Equation 6.5 (AOAC, 1995; method 965.33).

$$Peroxide\ value = \frac{S\ x\ N\ x\ 1000}{Weight\ of\ sample\ (g)} \quad (6.5)$$

where S is the ml $Na_2S_2O_3$ (Test-Blank) and N is the normality of $Na_2S_2O_3$

6.2.4.4. Microbial analysis

Meat samples (25 g) were mixed in sterile glass jars containing 225 ml of sterile 0.85% saline solution for 2 min. Decimal serial dilutions were prepared using saline solutions; 0.1 ml aliquots of the dilutions were subsequently spread over the surface of plates in triplicates. Culture media and incubation conditions used for the different microbial groups were as follows: total viable count on pour plates of plate count agar (PCA) at 35 °C for 48 h-AOAC official method 966.23 (AOAC, 2000); Yeasts and moulds on Potato Dextrose Agar (PDA), acidified with lactic acid to pH 3.5, at 35 °C for 3 days (Guizani et al. 2002); *Staphylococcus aureus* on Baird-Parker agar at 35 °C for 48 h (ISO 6888-1:1999); *Salmonella* on Xylose-Lysine-desoxycholate (XLD) agar at 35 °C for 24 h (ISO 6579); *Enterobacteriaceae* on Violet Red Bile Glucose (VRBG) agar at 35 °C for 24 h (ISO 21528-1:2017) and *Listeria monocytogenes* on Listeria selective medium at 35

°C for 24 h (ISO 11290-1:2004). The results were expressed as Log_{10} colony-forming units per gram (log_{10} cfu/g) of dried meat.

6.2.5. Statistical analysis

In order to determine the effect of drying methods on physico-chemical and sensory quality characteristics of dried beef, the experiments were designed as a single factor completely randomized design. The results were subjected to one-way analysis of variance and differences in treatment means identified at $p \leq 0.05$ by Duncan's Multiple-range Test using GenStat Edition 13 software (VSN International Ltd, UK). To establish the effects of packaging type and storage time on the chemical and microbial quality characteristics of dried beef, a 4 x 5 factorial arrangement was used with packaging type and storage time as the experimental variables. The data were analysed using MINITAB version 16 software (Minitab Inc, Pennsylvania, USA). Analysis of variance was carried out and the p-value used to determine significance of main effects and interaction between variables at $\alpha \leq 0.05$, $\alpha \leq 0.01$ or $\alpha \leq 0.001$. To establish differences between means at $p \leq 0.05$, the experiments were designed as a single factor completely randomized design and one-way analysis of variance done using Duncan's Multiple-range Test and GenStat Edition 13 software (VSN International Ltd, UK). All the experiments were replicated three times.

6.3. RESULTS AND DISCUSSION

6.3.2. Effect of drying methods on the physico-chemical and sensory qualities of dried beef

6.3.2.1. Colour, moisture content and rehydration ratio

The results for colour, moisture content (m.c) and rehydration ratio (RR) for fresh and dried beef samples at different sections of the solar tunnel dryer (A, B, C and D) and in the open sun are shown in Table 6.1. The drying methods had significant effects on all the CIE colour values. The L*, a*, b*, C* and H* values of solar dried beef samples varied from 25.15±3.25 to 29.86 ±3.33, 2.98±0.77 to 4.16±0.79, 3.83±1.26 to 5.13±2.05, 49.11±9.07 to 52.84±15.85 and 4.96±0.96 to 6.41±1.45 respectively. Both the solar and sun dried beef samples had significantly lower ($p \leq 0.05$) L*, a*, b* and chroma (C*) values and higher Hue angle (H*) compared to fresh beef, which indicated that the drying methods caused changes to the protein structure of meat samples (Lawrie, 1998). The extent of these reactions in solar drying may have been more pronounced, resulting in darker meat compared to sun dried samples. This could be attributed to the higher temperatures encountered during solar drying compared to open sun drying.

However, analysis of variance of the results indicated that the observed differences in colour between the sun and solar dried beef samples was only significant ($p \leq 0.05$) for Lightness (L*) and saturation index/chroma (C*) in the sample closest to the collector section of the tunnel dryer (sample A). This could be explained by the fact that the gradual change in surface colour from red to brown, encountered during sun and solar drying, was not only as result of thermal autoxidation of the red oxymyoglobin to brown rnetmyoglobin but also a combination of other factors including photochemical reactions (Fautsman and Cassens, 1990) and oxygen availability (Renerre, 1990).

Table 6.1: Effect of drying methods on beef colour parameters, moisture content and rehydration ratio

	Fresh Beef	Solar dried samples A	B	C	D	Sun dried Samples
Colour						
L	33.08±0.73^{c}	25.15±3.25^{a}	29.28±5.53^{ab}	29.86±3.33^{b}	28.15±3.70^{ab}	31.86±3.57^{b}
a*	14.96±1.14^{b}	2.98±0.77^{a}	3.52±0.80^{a}	4.16±0.79^{a}	3.13±0.68^{a}	4.20±2.39^{a}
b*	8.17±0.20^{b}	3.83±1.26^{a}	5.13±2.05^{a}	5.01±1.63^{a}	4.04±1.34^{a}	5.38±1.84^{a}
H*	28.70±2.01^{a}	51.01±12.49^{b}	52.84±15.85^{b}	49.11±9.07^{b}	51.24±9.89^{b}	53.26±20.66^{b}
C*	17.06±0.99^{d}	4.96±0.96^{a}	6.41±1.45^{bc}	6.57±1.56^{bc}	5.17±1.20^{ab}	7.28±1.31^{c}
m.c	75.57±5.71^{f}	2.31±0.23^{a}	8.73±0.16^{d}	7.93±0.23^{c}	5.98±0.10^{b}	19.85±0.44^{e}
RR		1.28±0.05^{b}	1.26±0.04^{ab}	1.24±0.03^{ab}	1.27±0.04^{b}	1.20±0.05^{a}

Means in the same column with the same superscripts are not significantly different at $p > 0.05$; mc moisture content; RR rehydration ratio; A, B, C and D represent beef samples dried from the collector end to the end of the solar dryer respectively.

The moisture content of all the samples dried in the open sun and in the solar tunnel drier (at all the sections) differed significantly ($p \leq 0.05$). However, the rehydration ratio of sun dried beef samples was significantly lower ($p \leq 0.05$) than that of samples A and D in the solar tunnel dryer. It is generally accepted that the degree of rehydration is dependent on the degree of cellular and structural disruption in food systems which is correlated severity of the drying process. This decreases the specific volume of the product and intensifies shrinkage (Yan *et al.*, 2008). However, the high temperatures experienced in the solar drier resulted in the phenomenon of case hardening at the meat surface due to coagulation of myofibril proteins (mostly occurring at 50 °C) (Chabbouh *et al.*, 2011). With the continued drying to low moisture contents (2.31±0.23% and 5.98±0.10% for sample A and D respectively) and at higher temperatures above 60 °C in the solar tunnel dryer, the vapour pressure inside the samples increased and expanded to create larger voids. This could have been enhanced by the transverse shrinkage of muscle fibres and connective tissue fibres beginning at temperatures of 60 °C resulting in increased uptake of water for the solar dried beef samples. Similar results have been reported for chicken meat by Nathakaranakule *et al.* (2007).

6.3.2.2. Instrumental texture

Hardness and firmness of dried and dried-rehydrated beef samples

The mean values of hardness (N) of solar dried and open sun dried beef samples as measured by puncture test (x 10) and texture profile analysis are given in Figure 6.4. The firmness results (N) as given by the volodkevich method are also shown. The instrumental texture parameters of hardness/firmness/softness measure the scale of resistance of food to applied compressive forces. The textural properties of hardness and firmness of foods are closely related and the boundaries between them instrumentally are not yet known (Szczesniak, 2002). The hardness values of the solar dried slices obtained for the puncture test and texture profile analysis ranged from 3.50±0.11 to 4.47±0.07 and 25.08±4.99 to 33.04±5.73 N respectively while the firmness values of the volodkevich bite jaws test ranged from 32.93±1.81 to 46.60±0.99 N.

The puncture test hardness values were significantly lower ($p \leq 0.05$) than the values found for all the test methods used and were approximately ten times lower than the volodkevich firmness values. This could be explained by the fact that the puncture test was used to assess the crust penetration force and inner tissue firmness of the dried product (Alvares *et al.*, 2000) whereas the TPA and volodkevich imitative tests were used to determine resistance to the compressing forces (Szczesniak, 2002). The TPA test could only be done on rehydrated samples resulting in a lower force of compression compared to the force required to deform samples for the volodkevich test. However, there was a high level of variability of the results as given by the large values of standard deviation of the TPA samples. This could have been caused by the irregular structure of the samples as a result of shrinkage even after 20 minutes of rehydration. De Huidobro *et al.* (2005) compared the Warner-Bratzler shear test and TPA method to determine the sensory characteristics associated with the texture of fresh beef and indicated that the TPA test predicted the sensory hardness better than the Warner-Bratzler test. According to Saláková (2012), TPA tests need to be performed on samples with a smooth flat surface so that the area in contact with the plate is known and constant.

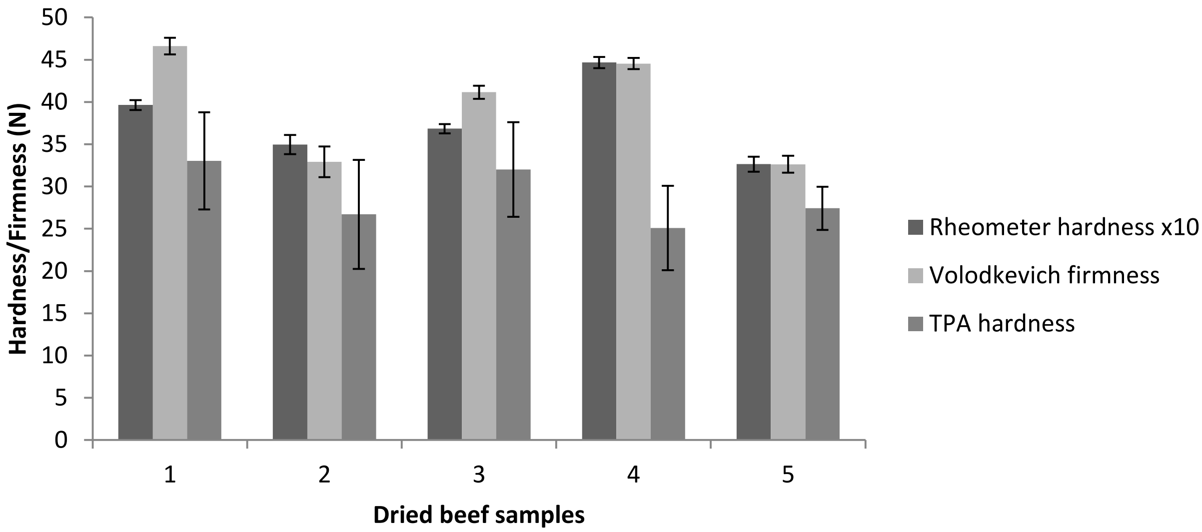

Figure 6.4: Comparison of hardness and firmness of beef using three instrumental methods.
The sample numbers 1-4 represent samples dried in the different sections of the solar dryer (A-D) respectively, while sample 5 represents sundried beef samples. Each value is expressed as mean ± standard deviation (n=3).

The texture values (rheometer hardness and volodkevich firmness) of the sun dried beef were significantly lower ($p \leq 0.05$) than those of solar dried beef samples, particularly for samples at the extreme ends of the solar tunnel dryer (sample A and D). When drying was performed at higher temperatures, a substantial increase in force for puncturing or compressing beef slices was observed, possibly due to the formation of an intensive crust layer on the surface. This toughness was primarily due to aggregation of muscle protein, especially actomyosin, by crosslinking (Byrde and Sands, 1981). The high moisture content of the sun dried beef could also have resulted in more tender meat. Youssef *et al.* (2007) related the moisture content with shear values, and observed that the higher the moisture content the more the tenderness of charqui meat. The authors indicated that moisture content was the primary cause of charqui meat texture. The effect of the moisture content on the compressive behavior of dried materials was also assessed by Krokida *et al.* (1998). There was no significant difference ($p > 0.05$) in texture of rehydrated beef samples analysed by TPA.

Other texture profile analysis (TPA) parameters

Table 6.2 gives other instrumental texture profile analysis parameters for rehydrated sun and solar dried beef samples. The classification of textural terms for solids and semi-solids give rise to a profiling method of texture description, TPA applicable to both sensory and instrumental measurements. The adhesiveness of sun dried beef had an average value of -1.68±0.03 while solar dried beef samples had adhesiveness values of 0.00±0.00. Adhesiveness is normally given with a negative value and it describes the work necessary to overcome the attractive forces between the surface of the food and the surface of the other materials with which the food comes in contact (Szczesniak, 2002). The adhesiveness of sun dried beef could be attributed to the higher moisture content of the samples.

Table 6.2: Effect of drying methods on other texture profile analysis parameters of dried rehydrated beef samples

	Texture parameter				
Samples	Adhesiveness	Springiness	Cohesiveness	Chewiness	Resilience
Solar dried					
A	$0.00±0.00^{b}$	$2.91±3.19^{b}$	$0.88±0.01^{a}$	$90.38±129.51^{a}$	$0.79±0.13^{a}$
B	$0.00±0.00^{b}$	$0.90±0.06^{ab}$	$0.84±0.04^{a}$	$35.98±30.98^{a}$	$0.65±0.14^{ab}$
C	$0.00±0.00^{b}$	$1.08±0.88^{ab}$	$0.84±0.02^{a}$	$12.10±1.59^{a}$	$0.65±0.04^{ab}$
D	$0.00±0.00^{b}$	$0.95±0.08^{ab}$	$0.85±0.01^{a}$	$53.10±20.81^{a}$	$0.74±0.07^{ab}$
Sun dried	$-1.68±0.03^{a}$	$0.25±0.32^{a}$	$0.81±0.19^{a}$	$7.21±7.91^{a}$	$0.63±0.03^{b}$

Means in the same column with the same superscripts are not significantly different at $p > 0.05$.

Springiness and resilience values of sun dried beef were significantly ($p \leq 0.05$) lower compared to the solar dried samples. This could be attributed to the higher moisture content of the sun dried samples. Springiness can be related to how the food structure breaks during chewing. The meat structure in samples displaying high springiness values showed a better recovery and did not break or change as much during compression as samples with lower values (Purgahen *et al*, 2010). Similar results on effect of moisture content on springiness of meat samples have been reported by Rongrong *et al.* (1998) and Martinez *et al.* (2003) whereby springiness decreases with increase in moisture content. There was no significant difference ($p > 0.05$) between cohesiveness and chewiness of the solar and sun dried beef samples.

6.3.2.3. Sensory quality

Results of sensory analysis of beef samples dried using a solar tunnel dryer and open sun drying are shown in Table 6.3.

Table 6.3: Mean sensory analysis scores for cooked and uncooked beef samples dried using different methods

	Solar drying		Sun drying	
	Uncooked	Cooked	Uncooked	Cooked
Colour	5.6 ± 1.45^{a}	6.6 ± 1.76^{ab}	4.8 ± 1.74^{a}	6.00 ± 1.69^{b}
Odour	5.33 ± 1.35^{a}	7.07 ± 0.88^{b}	4.8 ± 1.78^{a}	6.47 ± 1.46^{b}
Flavour	nd	6.87 ± 1.25^{a}	nd	6.60 ± 1.92^{a}
Texture	nd	5.93 ± 1.44^{a}	nd	5.40 ± 2.13^{a}
Appearance	5.00 ± 1.65^{a}	6.87 ± 1.13^{b}	4.6 ± 1.99^{a}	6.20 ± 1.97^{b}
Overall acceptability	5.73 ± 1.03^{ab}	6.8 ± 1.15^{c}	5.07 ± 1.44^{a}	6.13 ± 2.00^{bc}

Means in the same row with the same superscripts are not significantly different at $p > 0.05$; nd no data.

Generally, solar dried beef samples scored well (above average) for all the sensory parameters evaluated for cooked and uncooked beef**.** The samples which were cooked after drying scored significantly higher ($p \leq 0.05$) than their uncooked counterparts for all drying methods. There was no significant difference ($p > 0.05$) in the colour scores of uncooked sun dried beef and those for solar dried uncooked samples. The odour scores for the uncooked sun and solar dried beef samples were significantly lower ($P \leq 0.05$) than the cooked samples. In addition, panellists stated that the dried uncooked samples had a slightly rancid flavour. Slight oxidation (rancidity) of the meat fats contributes to the typical flavour of dried meats and is acceptable (FAO 1995). Generally, all the sensory scores for cooked samples dried using different methods did not differ significantly ($P > 0.05$). The texture difference detected by the texture analyser during texture profile analysis (TPA) of rehydrated beef samples were also reported by panellists. The mean texture score for solar dried and cooked beef samples was 5.93±1.44 while the scores for sun dried beef were somewhat lower (5.40±2.13). However, the difference was not significant at ($P > 0.05$).

6.3.3. Effect of packaging type and storage time on the chemical and microbial quality of dried beef

6.3.3.1. Moisture content

The simple and interaction effects of packaging type and storage time on the moisture content of dried beef during storage are given in Table 6.4 and the changes in moisture during the storage period are shown in Table 6.5. Change in moisture content of dried products during storage is one of the most important quality deteriorating factors and use of high moisture barrier packaging materials is therefore advocated for long-term storage of dried foods (Adom *et al.*, 1996). There was a significant ($P \leq 0.05$) packaging method x storage time interaction effect on moisture content of the solar dried beef samples but the effect was more significant for sun dried beef samples ($p \leq 0.001$) (Table 6.4).

Table 6.4: Packaging method and storage time effects on moisture content of dried beef

	Solar dried samples				Sun dried samples
Effects	A	B	C	D	
Packaging method	***	***	**	***	**
Storage time	*	***	***	**	***
Packaging method x storage time	**	**	**	**	***
r^2	0.93	0.89	0.97	0.98	0.96

*$p \leq 0.05$; ** $p \leq 0.01$; *** $p \leq 0.001$; NS not significant at $p > 0.05$

The moisture changes of dried beef samples using the sun and solar drying methods were highest during the first day of accelerated storage. The sundried beef samples were the most unstable and lost moisture continuously during the storage period from 19.85±0.44 % (Table 6.1) to between 9.33±0.13 and 11.09±0.07 % (Table 6.5). The solar dried beef samples with low initial moisture content absorbed moisture as the storage period increased: From 2.31±0.23 % to a maximum of 9.57±0.13 % and from 5.98±0.10 % to a maximum of 9.45±0.10 % for samples A and D respectively. Solar dried samples C were the most stable inside all four packaging materials and their moisture content values varied from 7.02±0.08 to 9.64±0.06 % during storage. According to Yamaguchi *et al.* (1986) dried meat products need to have a stable moisture content to avoid changes in quality during storage.

Table 6.5: Effect of packaging method and storage time on the average moisture content of dried beef samples

Samples	Packaging method	Storage time (days)				
Solar dried samples		1	2	3	4	5
A	P1	6.27 ± 0.06^{cv}	6.48 ± 0.03^{bv}	7.27 ± 0.41^{abw}	8.97 ± 0.08^{hy}	8.28 ± 0.11^{efx}
	P2	6.97 ± 0.07^{dvw}	6.77 ± 0.07^{cv}	7.14 ± 0.13^{aw}	8.63 ± 0.04^{gx}	9.57 ± 0.13^{kly}
	P3	7.41 ± 0.04^{efw}	7.05 ± 0.10^{dv}	8.34 ± 0.18^{ex}	8.18 ± 0.07^{ex}	8.12 ± 0.04^{dex}
	P4	6.26 ± 0.07^{cv}	6.53 ± 0.20^{bv}	7.48 ± 0.11^{bcw}	7.06 ± 0.01^{ax}	7.53 ± 0.03^{ax}
B	P1	6.07 ± 0.11^{av}	6.25 ± 0.03^{av}	7.03 ± 0.07^{aw}	7.47 ± 0.13^{bx}	7.79 ± 0.04^{by}
	P2	7.03 ± 0.04^{dv}	7.83 ± 0.04^{fv}	9.08 ± 0.04^{gx}	9.72 ± 0.16^{jy}	9.64 ± 0.08^{ly}
	P3	6.98 ± 0.04^{dv}	8.09 ± 0.10^{ghw}	8.38 ± 0.10^{exy}	8.47 ± 0.07^{fy}	8.27 ± 0.03^{efgwx}
	P4	7.89 ± 0.13^{gw}	7.36 ± 0.07^{ev}	7.77 ± 0.08^{dw}	8.37 ± 0.07^{fx}	8.55 ± 0.01^{hx}
C	P1	7.39 ± 0.06^{efv}	8.96 ± 0.11^{iy}	8.68 ± 0.10^{fx}	7.96 ± 0.04^{dw}	7.92 ± 0.08^{bcw}
	P2	7.98 ± 0.06^{gv}	8.20 ± 0.10^{hw}	9.45 ± 0.06^{hx}	9.31 ± 0.03^{ix}	9.64 ± 0.06^{kly}
	P3	7.52 ± 0.08^{fv}	8.01 ± 0.10^{fgw}	8.36 ± 0.07^{ex}	8.96 ± 0.08^{hy}	8.94 ± 0.03^{iy}
	P4	7.30 ± 0.03^{ew}	7.02 ± 0.08^{dv}	7.20 ± 0.11^{abvw}	7.17 ± 0.06^{avw}	7.92 ± 0.10^{bcx}
D	P1	6.11 ± 0.10^{abv}	6.60 ± 0.03^{bcw}	7.46 ± 0.07^{bcx}	8.75 ± 0.06^{gx}	8.45 ± 0.01^{ghy}
	P2	7.05 ± 0.04^{dv}	7.87 ± 0.08^{fw}	8.35 ± 0.04^{ex}	8.73 ± 0.06^{gy}	9.45 ± 0.10^{jkz}
	P3	7.85 ± 0.06^{gx}	7.17 ± 0.07^{dv}	7.43 ± 0.10^{bcw}	7.75 ± 0.01^{cx}	8.34 ± 0.14^{fgy}
	P4	7.09 ± 0.06^{dv}	7.45 ± 0.04^{ew}	7.58 ± 0.07^{cdw}	7.56 ± 0.04^{bw}	8.01 ± 0.10^{cdx}
Sun dried samples	P1	15.27 ± 0.11^{jz}	14.31 ± 0.08^{ky}	13.98 ± 0.10^{kx}	12.47 ± 0.06^{mw}	11.04 ± 0.10^{nv}
	P2	13.45 ± 0.04^{hz}	13.71 ± 0.07^{jy}	12.72 ± 0.08^{ix}	10.68 ± 0.07^{kw}	9.33 ± 0.13^{jv}
	P3	14.73 ± 0.06^{iz}	13.78 ± 0.04^{jy}	13.14 ± 0.0^{jx}	11.47 ± 0.08^{lw}	10.42 ± 0.10^{mv}
	P4	16.89 ± 0.08^{kz}	15.78 ± 0.06^{ly}	13.35 ± 0.04^{jx}	12.61 ± 0.07^{mw}	11.09 ± 0.07^{nv}

Means with the same superscript letters in the same column (a-n) and in the same row (v-z) are not significantly different at $p > 0.05$.
P1, P2, P3, and P4 are glass, paper, polyethylene and aluminium foil respectively.

When a food product is exposed to an environment above or below its equilibrium point, the protective packages and its barrier level will determine how much its moisture content will be impacted (Esse and Saari, 2004). The moisture changes were significantly lower ($p \leq 0.05$) in the aluminium foil and glass packaging materials compared to paper and low density polyethylene (LDPE) packaging types. This was caused by the high rate of migration of water vapor of the latter from the storage environment into the packaging material and from the packaging material to the environment. This could have been caused by the higher permeability of polyethylene and paper to moisture as compared to aluminium foil wraps and glass jars as a result of their high water vapor transmission rate (WVTR) (Gopal *et al.*, 1998). This finding is in agreement with the work done on potatoes by Abong *et al.* (2011), who noted that aluminium foil provided better barrier to moisture transfer than polyethylene pouches.

The higher temperatures during accelerated storage could have resulted in a greater extent of moisture loss in polyethylene pouches. Temperature dependence of WVTR has been described with Arrhenius equation (Mannapperuma and Singh, 1994). At higher storage temperatures, WVTR of the flexible films became greater, resulting in the higher rate of changes in moisture content. When compared to glass, the advantages of paper as a packaging material are its low cost, wide availability low weight and printability, although its most serious shortcoming is its sensitivity to moisture (Miltz, 1992).

6.3.3.2. Peroxide value

The packaging and storage time effects on the peroxide value of stored dried beef are given in Table 6.6. Both packaging method and storage time significantly affected ($p \leq 0.001$) the peroxide value of the dried products.

Table 6.6: Packaging method and storage time effects on the peroxide value for dried beef

	Solar dried samples				Sun dried samples
Effects	A	B	C	D	
Packaging method	***	***	**	***	***
Storage time	***	***	***	***	***
Packaging method x storage time	**	**	*	**	***
r^2	0.95	0.90	0.87	0.98	0.94

*$p \leq 0.05$; ** $p \leq 0.01$; *** $p \leq 0.001$; NS not significant at $p > 0.05$

The peroxide value of dried beef after open sun drying was significantly lower ($p \leq 0.05$) (1.68±0.04 mEq/kg) compared to values for solar tunnel dried samples (3.47±0.03, 3.22±0.11, 3.41±0.05 and 3.21±0.03 mEq/kg for samples A, B, C and D respectively). This could have been due to a combination of many factors: The high temperatures encountered in the solar drier could have led to higher rate of deterioration of solar dried beef samples. It is known that heat treatment has negative effects on cellular structure, inactivates enzymes (including those with reducing activity) and releases oxygen from oxymyoglobin, creating conditions for hydrogen peroxide production (Kanner, 1994). Rahman *et al.,* (2005) related the peroxide value of meat dried using different methods to their porosity. As discussed earlier the larger voids of solar dried beef samples could have led to higher oxidation during drying. On the contrary, sensory analysis results of cooked samples (section 6.3.2.3) reported high flavour scores of solar dried beef indicating possibility of changes in flavour other than rancidity; which develop more rapidly in products with high moisture content (Kanner, 1994).

The change in peroxide values with time for sun dried and solar dried beef (sample A) under different packaging materials are given in Figures 6.5 and 6.6 respectively. The curves of lipid oxidation showed a similar trend in which a gradual increase in PV was observed from day 0 to day 5 in all the packaging systems.

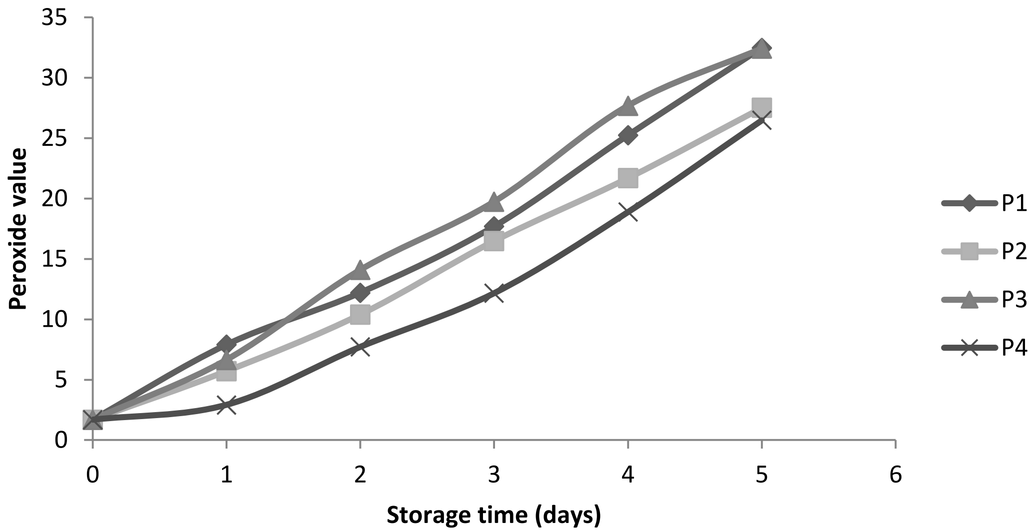

Figure 6.5: Changes in PV of sun dried beef during accelerated storage in different packaging materials (P1-glass, P2-paper, P3-polyethylene, P4-aluminium foil)

Other researchers have also observed an increase in PV during storage of lipid-containing food products (Pelser *et al.,* 2007; Vanhanen and Savage, 2006; Rhee *et al.,* 1999). This is due to the formation of hydroperoxides of unsaturated fatty acids that were obtained as a result of lipid oxidation. The peroxide values of the sun dried meat was very high and very close to the recommended value of between 20 and 40 mEq/kg for rancid taste to begin in dried or smoked meat and fish (Adeyeye, 2016). The lower levels of peroxide value of solar dried beef during storage (Figure 6.6) compared to open sun dried samples may be associated with its moisture content. Chen and Mujumdar (2009), reported on a number of hypothesis to explain the protective effect of water in retarding lipid oxidation. However, the continuous decrease in moisture content of sun dried beef samples during storage and the high temperatures of accelerated storage (55 °C), could have led to changes in protein structure (Mewa *et al.*, 2018) of the sun dried products and increased oxygen uptake thus a higher PV during storage.

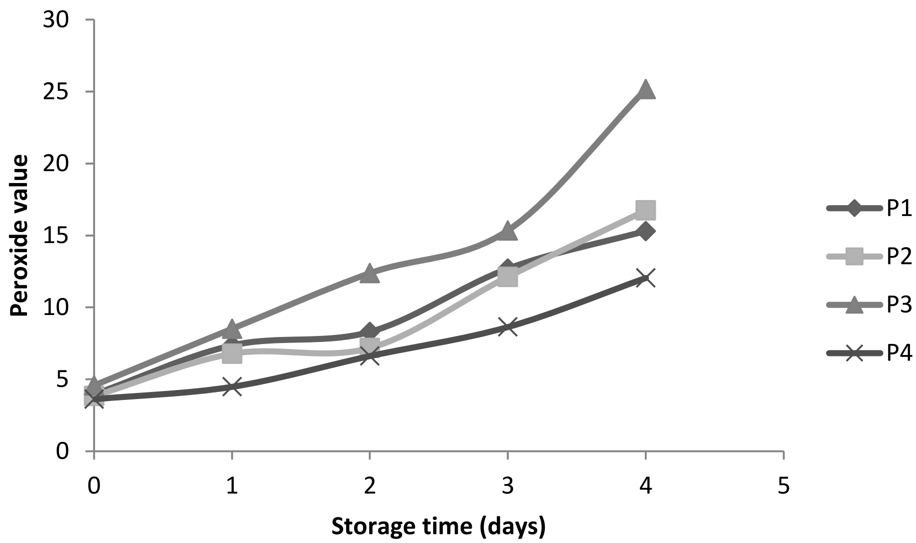

Figure 6.6: Changes in PV of solar dried beef (sample A) during accelerated storage in different packaging materials (P1-glass, P2- paper, P3- polyethylene, P4- aluminium foil)

The PV of the dried beef strips stored in aluminium foil packaging was lower than those stored in the glass, paper and polyethylene packaging. This difference could be attributed to two major factors; exposure to light and air. Transparent packaging materials allow more light to enter the product, which could have resulted in higher photo-oxidation rates of samples in glass and polyethylene packages. However the oxygen transmission rates (OTR) of the packaging materials could have influenced the PV more (Presswood, 2012). In packaging films, OTR is a factor that can influence the package atmosphere of products (Xiao *et al*. 2014). The higher oxygen transmission rates of polyethylene films compared to the other packaging materials could have resulted in higher lipid oxidation of the products.

6.3.3.3. Microbial quality

The initial microbiological characteristics of dried beef samples are shown in Table 6.7. The different drying techniques varied in their lethality to the microflora. The total viable count, *Staphylococcus aureus* and yeasts and moulds were significantly higher ($p \leq 0.05$). in the open sun dried samples compared to the solar dried beef samples. The high temperatures within the solar tunnel dryer compared to open sun drying caused faster dehydration of the product thus inhibiting microbial growth. No significant growth (< 2.00±0.00 $\log_{10}$ cfu/g) of *Staphylococcus aureus* was observed in all the solar dried beef samples while the numbers were significant (3.66±0.11 $\log_{10}$ cfu/g) in the sun dried samples. Stapylococci are part of microflora present in the human body and a good indicator of contamination due to poor personnel hygiene practices (Nester *et al*., 2001). The use of a mechanical meat slicer minimized handling of the meat during preparation for drying. The temperatures encountered during open sun drying (21.3-38.9°C) were conducive for growth of the *Staphylococcus aureus* and their numbers were higher. Similar results were reported by Rahman *et al.*, 2005.

Table 6.7: Mean bacterial counts for fresh and dried beef samples

	Entero-bacteriaceae	*Salmonella*	*Listeria mono Cytogenes*	TVC	*Staphylococcus aureus*	*Yeasts and moulds*
Solar dried						
A	ND	ND	ND	3.24 ± 0.03^{a}	<2.00±0.00	ND
B	ND	ND	ND	3.72 ± 0.02^{a}	<2.00±0.00	ND
C	ND	ND	ND	3.41 ± 0.02^{a}	<2.00±0.00	ND
D	ND	ND	ND	3.00 ± 0.04^{a}	<2.00±0.00	ND
Sun dried	ND	ND	ND	4.87 ± 0.05^{b}	3.66±0.11	2.73±0.03

Microbial counts expressed as Log_{10} cfu/g; means in the same column with the same superscripts are not significantly different at $p > 0.05$; ND not detected.

The presence of yeasts and moulds on the meat samples immediately after drying (Table 6.7) suggested that these microorganisms were present on the original meat samples and survived the drying processes (Rahman *et al.,* 2005). *Enterobacteriacea*, *Salmonella* spp and *Listeria monocytogenes* were not detected in any of the samples.

The dried products were stored at accelerated temperatures of 55 °C and the only microbial characteristics that had significant growth during storage were total viable counts (TVC), yeast and moulds, *Listeria monocytogenes* and *Staphylococcus aureus*. The growth of *Listeria and Staphylococus* species only occurred in sun dried beef samples in paper packaging after 3 and 4 days of storage respectively. The numbers of *Listeria monocytogenes* were between 3.550±0.10 and 3.898±0.14 $\log_{10}$ cfu/g whereas the staphylococci numbers were 3.661±0.05 and 3.883±0.03 $\log_{10}$ cfu/g after 4 and 5 days of storage respectively. The packaging method and storage time effects on the TVC of dried beef samples are shown in Table 6.8. There was a significant (packaging method x storage type) interaction effect ($p \leq 0.05$) for all the dried beef samples and packaging method had a more significant effect ($p \leq 0.001$) on the total viable counts of all the samples dried using different methods.

Table 6.8: Packaging method and storage time effects on the total viable counts of dried beef

	Solar dryer sections				
Effects	A	B	C	D	Sun drying
Packaging method	***	***	***	***	***
Storage time	NS	*	*	**	***
Packaging method x storage time	**	*	**	***	***
r^2	0.90	0.96	0.87	0.94	0.92

*p ≤ 0.05; ** p ≤ 0.01; *** p ≤ 0.001; NS not significant at p > 0.05

Changes in TVC on dried beef during storage are shown in Table 6.9. Total Viable Count (TVC) or Aerobic Plate Count (APC) describes a measure of bacteria in the sample that can survive in the conditions on the surface of carcasses or in processed meat, be harvested by the sampling procedure used and grow in the presence of air on an agar plate. Because TVC also includes the organisms responsible for spoilage of meat, it gives an indication of the keeping quality of the product. All the dried beef samples during the period of storage had had total viable counts less than 4.00 $\log_{10}$ cfu/g. This was acceptable when compared to suggested limits of 2.5×10^5-1.0×10^8 (cfu/g) for dried meats (Chukwu and Imodiboh, 2009). The results indicated no spoilage of the dried beef during the storage period. The shelf life of the samples stored under accelerated conditions would thus be more than six months (where: 1 day of accelerated storage represents 37 days at room temperature).

The number of total viable counts in all the samples decreased on exposure to the accelerated temperature conditions in various packaging systems and the lag phase was extended for the solar dried beef samples. There was a gradual increase in the microbial populations with time for the solar dried and open sun dried beef. However, the increase was not significant at ($p > 0.05$) for most of the samples and for all the samples between the 4^{th} and 5^{th} days of storage. According to (Brown and Willams, 2003) results on accelerated shelf life tests should be interpreted with care because they are product specific. The accelerated temperatures may cause changes in the physical state and loss in moisture content of the product. Furthermore microorganisms grow at different temperatures (Hough, 2010). This could have caused a decrease in microbial growth on exposure to accelerated temperature conditions and decline in microbial populations after 4 days of storage.

Table 6.9: Effect of packaging method and storage time on the total viable counts (TVC) of dried beef samples

Solar dryer sections	Packaging method	Storage time (days)				
		1	2	3	4	5
A	Glass	ND	ND	2.45 ± 0.04^{abx}	2.46 ± 0.02^{ax}	2.48 ± 0.13^{ax}
	Paper	ND	ND	2.659 ± 0.08^{efgx}	2.73 ± 0.07^{bcx}	2.83 ± 0.07^{bcdefx}
	Plastic	ND	2.65 ± 0.06^{cx}	2.59 ± 0.02^{cdex}	2.671 ± 0.04^{abcx}	2.73 ± 0.11^{abcdex}
	Foil	ND	ND	2.45 ± 0.04^{abcx}	2.865 ± 0.05^{cdy}	2.99 ± 0.17^{defghy}
B	P1	ND	ND	2.34 ± 0.06^{ax}	2.49 ± 0.03^{ax}	2.65 ± 0.15^{abcx}
	P2	$<2.00\pm0.00$	3.05 ± 0.05^{dey}	3.31 ± 0.02^{my}	3.10 ± 0.37^{ey}	3.40 ± 0.19^{ijy}
	P3	ND	$<2.00\pm0.00$	3.23 ± 0.01^{lmx}	3.16 ± 0.13^{ex}	3.29 ± 0.17^{hijx}
	P4	ND	ND	2.95 ± 0.06^{ijx}	3.00 ± 0.00^{dexy}	3.12 ± 0.03^{fghiy}
C	P1	ND	ND	2.34 ± 0.06^{ax}	2.47 ± 0.01^{ax}	2.57 ± 0.16^{abx}
	P2	ND	ND	2.85 ± 0.01^{hix}	3.02 ± 0.08^{dex}	3.25 ± 0.08^{hijx}
	P3	ND	2.45 ± 0.04^{bx}	2.79 ± 0.08^{ghy}	2.84 ± 0.09^{cdxz}	3.06 ± 0.11^{fghz}
	P4	ND	ND	2.61 ± 0.01^{defx}	2.74 ± 0.05^{bcxy}	2.91 ± 0.05^{cdefgy}
D	P1	ND	ND	2.49 ± 0.02^{bcdx}	2.58 ± 0.05^{abx}	2.68 ± 0.19^{abcdx}
	P2	ND	2.96 ± 0.04^{dx}	3.06 ± 0.03^{jkxy}	3.21 ± 0.03^{eyz}	3.30 ± 0.14^{hijz}
	P3	ND	2.11 ± 0.06^{ax}	2.62 ± 0.02^{defy}	2.82 ± 0.04^{cdyz}	3.01 ± 0.22^{efghz}
	P4	ND	ND	2.69 ± 0.01^{efgx}	2.76 ± 0.02^{bcxy}	2.97 ± 0.15^{cdefghy}
Sun drying	P1	2.45 ± 0.07^{ax}	2.45 ± 0.14^{bx}	2.742 ± 0.06^{fghy}	2.88 ± 0.03^{cdyz}	3.09 ± 0.06^{fghiz}
	P2	3.08 ± 0.11^{bx}	3.40 ± 0.25^{fxy}	3.48 ± 0.16^{nxyz}	3.58 ± 0.06^{fyz}	3.89 ± 0.19^{kz}
	P3	2.505 ± 0.05^{ax}	3.28 ± 0.11^{efy}	3.34 ± 0.00^{my}	3.42 ± 0.05^{fyz}	3.53 ± 0.05^{jz}
	P4	2.580 ± 0.05^{ax}	2.88 ± 0.06^{cdy}	3.15 ± 0.03^{klz}	3.15 ± 0.00^{ez}	3.23 ± 0.15^{ghijz}

Microbial counts expressed as $\log_{10}$ cfu/g; means with the same superscript letters in the same column (a-n) and in the same row (x-z) are not significantly different at $p > 0.05$; P1, P2, P3, and P4 are glass, paper, polyethylene and aluminium foil respectively; ND not detected.

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There was a positive relationship between the TVC and the residual water content of the samples during storage. Following five days of storage, the level of microbial contamination measured on sun dried meat remained significantly higher ($p \leq 0.05$) than the levels on meat dried using solar drying technique. This could be attributed to the higher moisture content of sun dried beef which resulted in a higher water activity of the product at the same temperature and reduced stability to microorganisms compared to solar dried beef slices.

Data from the experiments (Table 6.9) clearly shows that storage either in glass jars or aluminium foil wraps was better for long term storage of dried beef as the total viable counts were significantly lower ($p > 0.05$) compared to polyethylene and paper packaged samples. This might have been due to the higher permeability of the latter to air and water vapour. Bacteria grow much more slowly in the absence of oxygen (Yilmaz and Demirci, 2010) and their growth in impermeable packages is dependent upon the atmosphere in the package and is characterized by longer lag phases (Ščetar *et al.*, 2010). Higher quality deterioration in polyethylene packed samples compared to glass jars was also reported by Sharma *et al.* (2000).

Yeast and mould growth was not detected in all the beef samples after one day of storage in different packaging systems. Table 6.10 shows the growth of yeast and moulds in dried beef samples after two to five days of storage. Treatments with higher initial moisture contents after drying (solar dried sample B and sun dried products) showed higher microbial counts which may be indicative of higher contamination levels and shorter shelf life. It is possible that the higher water content of these treatments may have favoured the development of these microorganisms. On the other hand, a majority of yeasts and moulds are mesophilic and can grow at temperatures within the range of 10-35 °C and some can grow at 45 °C or higher, thus could withstand the accelerated storage conditions.

Table 6.10: Effect of packaging method and storage time on the yeast and mould numbers in dried beef samples

Solar dryer sections	Packaging method		Storage time (days)		
		2	3	4	5
A	Glass	ND	ND	ND	
	Paper	ND	ND	ND	2.36 ± 0.08^{a}
	Plastic	ND	ND	ND	<2.00±0.00
	Foil	ND	ND	ND	<2.00±0.00
B	P1	ND	ND	ND	<2.00±0.00
	P2	2.52 ± 0.15^{ax}	2.56 ± 0.06^{bcx}	2.57 ± 0.05^{ax}	2.70 ± 0.01^{bx}
	P3	ND	2.45 ± 0.03^{abx}	2.59 ± 0.02^{ay}	2.64 ± 0.06^{bz}
	P4	ND	ND	ND	2.55 ± 0.08^{b}
C	P1	ND	ND	ND	<2.00±0.00
	P2	ND	ND	ND	2.87 ± 0.04^{c}
	P3	ND	ND	ND	2.55 ± 0.08^{b}
	P4	ND	ND	ND	<2.00±0.00
D	P1	ND	ND	ND	<2.00±0.00
	P2	ND	ND	ND	2.85 ± 0.01^{c}
	P3	ND	ND	ND	2.70 ± 0.11^{b}
	P4	ND	ND	ND	2.21 ± 0.13^{a}
Sun drying	P1	ND	ND	ND	<2.00±0.00
	P2	2.61 ± 0.01^{ax}	3.02 ± 0.08^{ey}	3.07 ± 0.07^{cy}	3.03 ± 0.03^{cy}
	P3	<2.00±0.00	2.73 ± 0.07^{dx}	2.75 ± 0.04^{bx}	2.61 ± 0.01^{bx}
	P4	<2.00±0.00	2.31 ± 0.01^{ax}	2.43 ± 0.05^{axy}	2.57 ± 0.05^{by}

Microbial counts expressed as $\log_{10}$ cfu/g; means with the same superscript letters in the same column (a-e) and in the same row (x-z) are not significantly different at $p > 0.05$; P1, P2, P3, and P4 are glass, paper, polyethylene and aluminium foil respectively; ND not detected.

The numbers of yeast and moulds in the beef samples were significantly higher ($p \leq 0.05$) after five days of storage (Table 6.10). According to Mothershaw *et al.* (2003) diversity of the moulds increases during storage and are recognized for their ability to survive rapidly changing environmental conditions. This suggests that these species were secondary contaminants, contaminating the food not at the source or during production, but during storage. This might have led to the increase in microbial levels with storage at accelerated shelf life conditions.

However, these levels were still acceptable because according to Health Protection Agency, (2009), dried, ready-to-eat raw food, including dried meat, with acceptable quality should contain less than 10^6 cfu/g yeasts and 10^4 cfu/g of moulds.

6.4. CONCLUSIONS

In terms of physico-chemical characteristics of dried beef, solar dried beef samples are darker, have higher rehydration ratio, hardness (N), firmness (N), springiness (%) and resilience and lower moisture content (%) and adhesiveness compared to sun dried beef samples. The cooked solar dried products therefore scored higher in all sensory quality attributes including texture, due to its high rehydration ratio. Beef samples dried in the middle of the solar tunnel drier (sample C) are more stable during storage in relation to moisture content. The peroxide value of dried beef after open sun drying are lower compared to values of solar tunnel dried samples but become higher during storage in accelerated temperature conditions. The PV increases gradually during storage in all the packaging systems. All the dried beef samples during the period of storage have total viable counts and yeast and mould numbers lower than the acceptable limits, indicating that the shelf life of the solar and sun dried beef strips can be more than six months. However, the microbial counts are higher in sun dried beef compared to solar dried. Packaging either in glass jars or aluminium foil wraps is better for long term storage of dried beef due to stable moisture content and lower PV and microbial growth.

CHAPTER 7: GENERAL CONCLUSIONS AND RECOMMENDATIONS

7.1. GENERAL CONCLUSIONS

Desorption isotherms of beef are sigmoid shaped, type II isotherms with the GAB and Oswin models having the best fit and net isosteric heat of sorption increasing with decrease in moisture content. Drying temperatures of 40-60°C in a laboratory simulated dryer are able to reduce the moisture content of beef with 0.25-1.0 cm slice thickness to less than 20% (stable moisture content). Page model adequately represents the drying behavior of beef in a laboratory simulated dryer as well as in a solar tunnel dryer and the effective moisture diffusivity of solar tunnel dried beef varies from 2.282×10^{-10} to 2.536×10^{-10} m/s^2. The chemical, physical, microbiological as well as sensory quality parameters are significantly affected during beef drying processes (at temperatures ranges of between 30 °C and 64 °C) and packaging in glass jars or aluminium foil wraps is better for long term storage of dried beef due to stable moisture content, lower fat oxidation and microbial growth.

7.2. RECOMMENDATIONS

In order to have sustainable livestock production in the arid and semi-arid areas of Kenya, more attention should be given to commercialization of beef products. The government could devote more resources to beef processing strategies through training of pastoralists in these areas on sustainable methods of meat preservation and provision of subsidized credit to farmers. Further research regarding the changes in internal structure of beef should involve the use of optical spectroscopy methods like the use of scanning electron microscopes that can show the changes in meat protein organization and structure. Future research on the shelf life of dried beef strips should be done at accelerated temperatures that cause minimal changes in the meat structure and do not inhibit microbial growth. However, storage at ambient temperatures for real time shelf life studies would be more ideal. Furthermore, sensory analysis to determine consumer acceptability thresholds should be included in the shelf life studies. Finally, in order to select packaging materials with a view to control meat deteriorative changes and with regard to economy as well as ready availability, the use of flexible laminates with multilayers that are impermeable to gas and water vapours should also be considered. Evaluation of adsorption isotherms would also be recommended in order to better understand the water to solids relationships during storage of dried beef under different conditions.

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Annex 1: Sensory analysis score sheet

You are receiving dried beef and dried cooked beef samples. Please assess the coded samples and indicate, based on the scale below, the degree of liking for each of the attributes.

9. Like extremely
8. Like very much
7. Like moderately
6. Like slightly
5. Neither like nor dislike
4. Dislike slightly
3. Dislike moderately
2. Dislike very much
1. Dislike extremely

Dried beef

Attributes	**Sample codes**		
	396	**145**	**872**
Colour	________	________	________
Odour	________	________	________
Appearance	________	________	________
Overall acceptability	________	________	________

Dried cooked beef

Attributes	**Sample codes**		
	917	**384**	**652**
Colour	________	________	________
Odour	________	________	________
Flavour	________	________	________
Texture	________	________	________
Appearance	________	________	________
Overall acceptability	________	________	________

Comments: ____

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