# INFRARED DRYING OF BILTONG: EFFECT OF PRE-TREATMENT AND DRYING CONDITIONS ON THE DRYING CHARACTERISTICS AND PRODUCT QUALITY

by

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Submitted in fulfilment of the requirements
for the degree of MScEng

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Pietermaritzburg
July 2014

# ABSTRACT

In this study, the drying kinetics of biltong was investigated under infrared and convective drying systems, with two product pre-treatment conditions namely, slice thickness and marinating duration. The effect of these treatments on the quality and microbiological food safety of biltong was investigated. In addition, the study sought to establish and compare the energy efficiencies of the infrared drying systems under investigation.

The drying of biltong was conducted under two infrared drying conditions (2.5 μm and 3.5 μm peak wavelengths) and a convective drying condition that mimicked conventional and commercial drying conditions at a temperature of 25$^{o}$C and 60% relative humidity. The two infrared heating systems were set so that they had the same intensity of 4777 W.m$^{-2}$ at the product surface, but different peak wavelengths (2.5 μm and 3.5 μm). The marinated products were dried from a moisture content of 73.99% ± 1.46% wet basis (wb) to the commercial quality requirement of 20% ± 1% wb. Samples had a product thickness of 5, 10 or 15 mm, and had been marinated for durations of 6, 12 or 24 hours prior to drying. The experiments were arranged in a complete randomized block design.

The drying rate, product temperature, quality attributes, such as colour, texture, shrinkage, rehydration, as well as total viable bacterial counts were measured, along with the infrared power consumption during the drying process.

It was observed that the infrared heater with a peak wavelength of 2.5 μm dried the products faster, when compared to the one with a peak wavelength of 3.5 μm at all times, even when the infrared intensity of both heaters on the products was the same. The convective drying system recorded lower drying rates and longer drying durations compared to the infrared heating systems. Increasing product thicknesses increased the drying times and reduced the drying rates for samples dried under the 2.5 μm peak infrared heater and the convective drying system. Increasing the duration of marinating, reduced the drying rates for samples dried under the convective air dryer and increased the drying rates for samples that were dried under the 2.5 μm peak infrared heater. The 3.5 μm peak infrared heater recorded varied results, but generally had the 10 mm thick and 12-hour marinated samples having higher drying rates for all samples dried under this system. The drying system used significantly ($p \leq 0.05$) affected the drying times, while the pre-treatment conditions had no significant ($p \geq 0.05$) effect on the drying times. The core temperature increased with decreasing product

thicknesses and increasing marinating duration for the 2.5 µm peak infrared heater. However, the 3.5 µm peak infrared heater product core temperature did not follow the same trend. This system recorded lower specific energy consumption (SEC) values, compared to the 2.5 µm peak infrared heater. Out of the five drying models tested, the drying kinetics of biltong was best described by the approximation of diffusion model (ADM) on the basis of the model's high coefficient of determination ($R^2$) and low root mean square error (RMSE) values. The sample lightness (L*) of dried samples was significantly ($p \leq 0.05$) influenced by the drying system. The convective air drying system recorded lower total colour difference (ΔE) values compared to the infrared systems. The L* a* b* colour parameters decreased after marinating fresh beef slices, and decreased even further after the drying process. Textural analysis showed lower hardness and puncture values for samples dried under the 2.5 µm peak infrared heater compared to the other drying systems. Samples dried under the 3.5 µm peak infrared heater recorded the highest shrinkage coefficient and rehydration rates. The three drying systems achieved at least a 2-log reduction in the total viable bacterial count, with the 2.5 µm peak infrared heater having the lowest most probable number (MPN) count of 7,020. The infrared drying systems produced biltong that had acceptable plate counts of *E-coli* less than $10^2$ CFU.$g^{-1}$. However, the convective air drying system did not meet this acceptability threshold for the safe consumption of biltong.

The samples that were dried under the 2.5 µm peak infrared heater recorded high drying rates, good microbiological safety and textural attributes compared to the convective and 3.5 µm peak infrared drying systems. However, this system had consumed more energy compared to the 3.5 µm peak infrared heater that produced biltong with superior shrinkage coefficient and rehydration characteristics as well as colour attributes that closely compared to those of samples dried under the convective air drying system. The study recommends both the 2.5 and 3.5 µm peak infrared heaters for the best texture of biltong, improved drying characteristics and enhanced microbial food safety of the product.

# PREFACE

I, Kipchumba Cherono, declare that:

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## SUPERVISORS' DECLARATION

Subject to the regulations of the School of Engineering, we, the Supervisors of the candidate, consent the submission of this thesis for examination.

Dr Gikuru Mwithiga

Prof. Tilahun Workneh

# ACKNOWLEDGEMENT

I am thankful to the Almighty God for giving me good health and strength, and for His guidance in the preparation of this thesis. I sincerely thank my Supervisor, Dr Gikuru Mwithiga, for his support in the research process, as well as his input and critique during the preparation of this document. I am equally grateful to Prof. Tilahun S Workneh for his guidance during the preparation of this document. I also thank Prof. Stefan Schmidt for his technical advice in experiments pertaining to microbiological food safety analysis.

My heartfelt gratitude goes to my family for their endless prayers, emotional support and for permitting me to be away from home for my studies.

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# LIST OF ABBREVIATIONS AND SYMBOLS

The following is a list of abbreviations, acronyms and symbols that are used throughout this thesis. It gives the acronym, abbreviation or symbol, its meaning and the page where it is used for the first time.

| Abbreviation | Meaning | Page |
|---|---|---|
| %RH | Percentage relative humidity | 42 |
| ADM | Approximation of diffusion model | 54 |
| ANOVA | Analysis of variance | 26 |
| Db | Dry basis | 8 |
| EMB | Eosin methylene blue | 53 |
| FIR | Far infrared | 16 |
| HA | Hot air | 20 |
| HWL | High wavelength | 46 |
| LSD | Least significant difference | 55 |
| LWL | Low wavelength | 45 |
| MIR | Mid infrared | 16 |
| MPN | Most probable number | 52 |
| MR | Moisture ratio | 11 |
| NIR | Near infrared | 16 |
| OH | Ohmic heating | 14 |
| POD | Peroxidase | 25 |
| PPO | Poly phenol oxidase | 25 |
| $R^2$ | Coefficient of determination | 22 |
| RF | Radio frequency | 14 |
| RMSE | Root mean square error | 22 |
| RTE | Ready-to-eat | 5 |
| SFD | Simplified Fick's diffusion model | 54 |
| SEC | Specific energy consumption | 55 |
| SIRDBD | Sequential infrared dry blanching drying | 23 |

| Abbreviation | Meaning | Page |
|---|---|---|
| SIRHA | Simultaneous infrared and hot air drying | 20 |
| SSL | Short shelf life | 5 |
| TOM | Total organic matter | 24 |
| TPA | Texture profile analysis | 50 |
| TVC | Total viable counts | 112 |
| Wb | Wet basis | 8 |
| w/w | Weight in weight | 41 |
| $\chi^2$ | Reduced chi square | 22 |
| L* | Lightness color parameter | 28 |
| a* | Redness color parameter | 28 |
| b* | Yellowness color parameter | 28 |
| $\Delta E$ | Total color difference | 25 |
| FAO | Food and agricultural organization | 35 |
| IR | Infrared | 2 |
| EMC | Equilibrium moisture content | 10 |
| $D_R$ | Drying rate | 11 |
| MEM | Modified exponential model | 23 |
| SE | Standard error | 23 |
| SS | Shelf-stable | 36 |
| AMSA | American Meat Society Association | 49 |
| CFU | Colony-forming unit | 113 |
| FSIS | Food Safety Inspectorate Services | 117 |
| USDA | United States Department of Agriculture | 117 |

# 1. INTRODUCTION

Drying of food and agricultural commodities is an important undertaking carried out as a preservation measure or as a means of conditioning products for further processing and handling steps. In engineering terms, drying of food and agricultural products is understood as a simultaneous heat and mass transfer process (Afzal and Abe, 2000), that aims at reducing the moisture of food products, in order to lengthen their shelf-life, as well as to enable other processing and handling steps to be carried out. Subsequent food and agricultural processing operations to this effect, therefore, depend heavily on the success of drying.

Different drying technologies have emerged alongside the traditional sun-drying technology, due to the advancement in food and crop drying research. Solar drying of agricultural and food products, uses solar energy to heat up products, by combining the processes of conduction and convection to achieve moisture reduction (Khir *et al.*, 2006).

Sun drying is the oldest drying technology. It involves the spreading and exposure of products on a flat surface to the sun's rays. Solar drying evolved from sun drying, where attempts to capture and concentrate the sun's radiation on the food to be dried is explored. Solar dryers consist of three basic parts; a collector, drying chamber and an air circulation system (Green and Schwarz, 2001). Configurations of solar dryers include direct solar dryers, indirect mode solar dryers, mixed mode solar dryers and hybrid solar dryers. Hybrid types combine solar heating with an additional heating source such as biomass or fossil fuels (Bhattacharya *et al.*, 2000; Murthy, 2009; Fudholi *et al.*, 2010). Different configurations of hybrid solar dryers have been discussed in detail by Fudholi *et al.* (2010). Food products can also be dried using other methods such as; spray drying, freeze drying, osmotic drying and vacuum drying.

Spray drying constitutes drying systems that are used to dehydrate slurries and purees (Vega-Mercado *et al.*, 2001; Gharsallaoui *et al.*, 2007) where drying is achieved by spraying the liquid to be dried into a hot medium, normally air. Fluidized bed drying is similar to spray drying, except that in this case, the solid food is dried in a stream of hot air in which it is suspended and conveyed (Vanecek *et al.*, 1966; Vega-Mercado *et al.*, 2001; Syahrul *et al.*, 2002).

Freeze drying and osmotic drying are technologies used to dry high value products. Freeze drying comprises of a freezing process and a sublimation step (King, 1971). Osmotic drying

utilizes differences in product concentrations to dry them, which, in some cases, is aided by a vacuum (Vega-Mercado *et al.*, 2001). Drying technologies that comprise of high vacuum systems, microwaves and radio frequency are some of the drying methods or technologies that are still under development (Goullieux and Pain, 2005; Pereira and Vicente, 2010) and mainly aim at reducing energy consumption and improving product quality.

Drying is an energy demanding process. Statistics (Mujumdar and Devahastin, 2000) show that in Canada, the USA, France and the UK, drying consumes 10-15% of the total national industrial energy demand as well as 20-25% of the total national industrial energy demand for Denmark and Germany. Kasmaprapruet *et al.* (2009) reported that the energy requirement for the drying phase during the production of milled rice in Thailand is 55% of the total energy consumed from seed production to consumption. Grain drying in the USA uses up to 15 million barrels of oil per year (Verma, 1999) to dry approximately 332 million tons of grain, and if the eating habits of the all the people in the world were the same as those of the Americans, the available global oil reserves would be exhausted on grain drying needs in 12 years (Billiris *et al.*, 2011).

Convective drying systems comprise of 85% of all industrial drying systems (Raghavan *et al.*, 2005). These systems have low drying efficiencies as their biggest limitation due to convective losses in heating and transportation of the working fluid. Fluck and Baird (1980) estimated the energy requirements for drying grain under ideal conditions to be between 2500 and 2670 $kJ.kg^{-1}$ of water. However, due to system inefficiencies, the energy requirement for this process may increase to between 3000 and 8000 $kJ.kg^{-1}$ of water (Gunasekaran and Thompson, 1986).With emerging global environmental challenges, courtesy of greenhouse gas emissions, there is an urgent need for energy-intensive processes such as drying, to evolve to the extent that every joule of drying energy is efficiently utilized (Madamba *et al.*, 1996; Mujumdar and Devahastin, 2000; Raghavan *et al.*, 2005).

Alternative drying technologies have been developed with maximizing energy efficiency as the objective. Some of the emerging drying technologies include; sonic-assisted drying, super-heated steam drying, heat pump-assisted drying and electro technologies (those that use electromagnetic waves to dry products) (Goullieux and Pain, 2005; Raghavan *et al.*, 2005; Pereira and Vicente, 2010; Rastogi, 2012). Radiative heating, using infrared (IR) energy, has produced promising results and there are currently a huge interest in its application to the drying food and agricultural materials.

Infrared heating energy is an electromagnetic radiation with a spectral range of 0.75 μm to 1000 μm, that is produced by any object above the temperature of absolute zero degrees (Krishnamurthy *et al.*, 2008; Jun *et al.*, 2011) and can be used to dry food and agricultural products. Some of the distinct advantages of infrared drying over conventional hot air drying include; the production of high quality products, high energy efficiency, high heat transfer rates and reduced drying time (Krishnamurthy *et al.*, 2008; Rastogi, 2012). The advantages of infrared drying can be summarized as follows: (a) it results in energy savings from improved drying efficiencies (Nowak and Lewicki, 2004; Basman and Yalcin, 2011; Ponkham *et al.*, 2012), (b) equipment used is compact (Nowak and Lewicki, 2004), (c) there is a high efficiency of heat transfer through air or vacuum (Nowak and Lewicki, 2004; Sharma *et al.*, 2005a; Shi *et al.*, 2008; Basman and Yalcin, 2011; Khir *et al.*, 2011; Ponkham *et al.*, 2012), (d) it has good prospects for automation (Nowak and Lewicki, 2004) and (e) has improved hygiene (Nowak and Lewicki, 2004). In addition, this technology is environmentally-friendly because of the elimination of waste heat, thus making it an attractive choice in food processing (Khir *et al.*, 2011).

Infrared drying, being an emerging research area, has been applied to dry different products (Krishnamurthy *et al.*, 2008). In addition, due to the nature and complexity of the composition and behaviour of food and agricultural materials, the application of research results carried out on a given product may not give valid conclusions for different products, since every food and agricultural material has unique characteristics. Understanding the behaviour of a product under infrared drying will confer the benefits of confidence in the design of a given drying system, allowing the scaling up of these designs to suit the high volumes of products processed under industrial settings.

Biltong is a meat-based snack that is very popular in South Africa. Different recipes are used for its preparation but it commonly undergoes a drying process after being spiced and salted. There are few published articles on the drying of biltong and most producers of biltong for house consumption usually utilize ambient conditions for drying their products. Electric heaters are also used by some of the middle level processors who supply their products to supermarkets and other retail outlets. These constitute conventional air drying methods that utilize heated air to dry the product. These drying methods require long drying times and pose serious challenges to the food quality and safety of biltong (Nortjé *et al.*, 2005). Long drying

times due to low processing temperatures and contact of the heated air on the products, increases the risk of microbial contamination occasioned by conventional drying of biltong.

Currently, there are no publications on infrared drying of biltong. The appropriate application of infrared drying to food products is known to have high drying rates and reduced drying times (Krishnamurthy *et al.*, 2008). This study seeks to investigate the drying parameters that have a reduced drying times and that increase the drying rates of infrared dried biltong products without appreciably altering its quality, so as to produce products the quality of which are comparable to that of convective air dried biltong, with improved microbiological safety attributes (Nortjé *et al.*, 2005; Burnham *et al.*, 2008; Naidoo and Lindsay, 2010).

## 1.1 Aims and Objectives

This study seeks to investigate the drying kinetics of biltong under different pre-drying treatments and drying conditions, and the effect of these on the resultant product quality.

The specific objectives are:

a) to investigate the effects of different product thickness, marinating levels and drying systems on the drying kinetics of biltong.
b) to compare the drying efficiencies of two infrared heaters with different peak emission wavelengths but operating at the same infrared intensity at the products' surface.
c) to investigate the combined effect of drying system and pre-treatment conditions on the quality of dried biltong.
d) to study the goodness of fit of drying data into well-established drying models.

## 1.2 Scope and Limitations

This study investigates the drying characteristics and quality of biltong of various product thickness (5, 10 and 15 mm) and marinating duration (6, 12 and 24 hours) that was then dried under three drying systems (convective air dryer, 2.5 μm and 3.5 μm peak infrared heaters).

Equipment, time and cost constraints have limited the scope of product quality analysis to exclude certain aspects of microbial and sensory analysis.

## 1.3 Roadmap of Study

This thesis is organized into five chapters. This chapter (Chapter One) gives a general overview of the study, detailing its justification and the objectives.

Chapter Two, the literature review, first gives the general definitions of terminologies and the importance of food drying in food processing and preservation. An overview of the important technologies used in food drying is briefly discussed. It discusses the fundamentals of infrared drying technology, as applied to food and crop drying, which is the central theme of investigation in this study. A review of food quality analysis methods in light of ready-to-eat (RTE) meat products and other short shelf life (SSL) food products is also discussed. This chapter finally presents a historical overview of meat drying, its importance, some of the dried meat products consumed in different parts of the world and climaxes on biltong, this being the product of investigation in this study. The research gaps with regard to biltong are highlighted with emphasis on challenges of its preservation when it is dried under conventional drying, its quality and food safety issues.

Chapter three details the materials used and methodologies adopted in the study. The methods used for data collection and analysis are also presented.

Chapter Four presents the research findings and details the implications of the analysed results.

The conclusion wraps up the final chapter, by highlighting the major findings of this work.

# 2. LITERATURE REVIEW

This chapter presents an overview of food drying as an important means of food preservation and reviews some of the commonly-used drying systems that are currently used in the food drying industry and emerging technologies that are currently under research. It focuses on infrared drying of food products, this being the drying method under investigation. Some of the methods used for analysing the quality of food products are also presented. Literature on important dried meat products produced across the globe is also reviewed with special emphasis on biltong; its production process and food quality problems associated with some of the conventional production processes.

## 2.1 Overview of Drying of Food and Agricultural Materials

Drying is one of the oldest and widely-used process in many engineering disciplines and applications. The process is used in diverse fields and industries, including chemical, agricultural, biotechnology, paper and pulp, pharmaceutical, mineral mining and processing, polymers, metals and wood products manufacturing processes (Mujumdar and Devahastin, 2000). Different definitions and descriptions of drying have been widely discussed in literature.

Mujumdar and Devahastin (2000) described drying as a process that converts solid, liquid or a semi-solid feedstock into a solid material through the evaporation of the liquid into vapour by application of heat. In other applications such as freeze drying, heat is supplied and it directly causes drying through sublimation. This definition does not include some special drying operations such as evaporation in cases where semi-solid media need to be concentrated, mechanical water removal processes, which include centrifugation, filtration, sedimentation, the drying of gases and liquids, using molecular sieves or extraction (Mujumdar and Devahastin, 2000). Toğrul (2005) described drying as a process for the removal of most of the water contained in a product or a material. Ilic and Turner (1986) defined drying as a process involving simultaneous heat and mass transfer, in which heat is supplied by an external source that evaporates and subsequently reduces moisture from a wet porous medium. McMinn and Magee (1999) described drying as a moisture removal process from solids and constitutes an integral element in food processing. They further qualified drying as a recognized and organized field of research in chemical engineering. Jangam and Mujumdar (2010) defined drying as one of the economical means of preserving foods of

many kinds in which water is removed by the application of heat. They also described it as a complex operation that involves the transient transfer of heat and mass along with several rate processes that includes chemical or physical changes which may bring about product quality changes. From these descriptions and definitions, drying can therefore, be termed as a heat and mass transfer process that is used to reduce the moisture in different materials. It is a food preservation approach with huge applications in food processing and handling.

The role of drying food has been described by Green and Schwarz (2001) as a process that minimizes food spoilage and is ideal for fruit preservation due to their high acid and sugar content. In their study where they investigated drying kinetics of kale, Mwithiga and Olwal (2005) indicated that drying of this vegetable is an important process that improves its storability for long periods of time without appreciably affecting the nutritive elements. Drying of vegetable products reduces their weight and therefore helps considerably in making their handling and haulage convenient (Mwithiga and Olwal, 2005). They also indicated that drying of this vegetable confers the benefit of product size reduction, hence minimizing space and storage requirements, as well as reducing price fluctuations in the market by ensuring a continuous supply when the crop is out of season (Mwithiga and Olwal, 2005).

Fudholi *et al.* (2010) described drying as an important post-harvest food handling operation which can lengthen the shelf-life of harvested products, improve its quality and empower the farmer through the provision of a better bargaining ground by maintaining relatively constant prices for the products as well as the reduction of post-harvest losses. Drying of food also reduces transport costs by the removal of the excess water from the products (Fudholi *et al.*, 2010).

Mujumdar and Devahastin (2000) summarized some of the benefits of drying agricultural and food commodities as follows: convenience in handling materials, preservation and storage, reduction in cost of transportation and enhancement of the quality of dried product.

Jangam and Mujumdar (2010) described drying as a process that mainly purposes to reduce or completely eliminate microbial spoilage in food materials which can occur during harvesting operations and storage, with the microbial agents commonly present in food being bacteria, protozoa and fungi. Insects also contribute to food losses in many ways. Food drying also reduces or eliminates enzymatic browning and lipid oxidation (Jangam and Mujumdar, 2010).

From the foregoing discussions, it can be seen that food and crop drying is one of the most important tools used by mankind since ancient times and it has enabled civilizations to exist and evolve to this day. Without food drying, its preservation, handling and subsequent processing operations could be difficult or even impossible, bringing with it serious challenges with regard to food availability.

## 2.2 Terminologies and Fundamentals

Every industry has its own terminology, fundamental principles and applicable technical jargon. The forthcoming discussion highlights some of the important terminologies relevant to drying of food and agricultural materials.

Moisture content is the single, most important measure that shows how much water is in a food material. It is expressed in terms of dry or wet basis and this is abbreviated as db or wb, respectively. The wet basis moisture is normally used in commercial applications, while the dry basis moisture content is used for engineering and research purposes. These terms are expressed mathematically, as shown in Equations 2.1 and 2.2.

$$M_d \quad \frac{(\quad_0 - \quad) -}{\quad} \tag{2. }$$

$$M_w \quad \frac{(\quad_0 - \quad) -}{+} \tag{2.2}$$

Where $M_d$ is the dry basis moisture content of the product in kg of water/kg of dry matter, $W_0$ is the initial mass of the sample in kg, W the mass of the water evaporated in kg, $W_1$ the mass of the dry matter in the sample in kg and $M_w$ is the wet basis moisture content in kg of water/kg of wet sample.

Khir *et al.* (2006) described the moisture content of rough rice as one of the most important factors that influence its storage, further handling and the resultant quality. For this reason, rough rice has to be adequately dried to safe storage moisture levels.

Equilibrium moisture content is described by Mujumdar and Devahastin (2000) as the moisture content of a wet solid material in equilibrium with the surrounding air at a given relative humidity and temperature. A plot of equilibrium moisture content verses relative humidity at a certain temperature is called a sorption isotherm and is as shown in Figure 2.1.

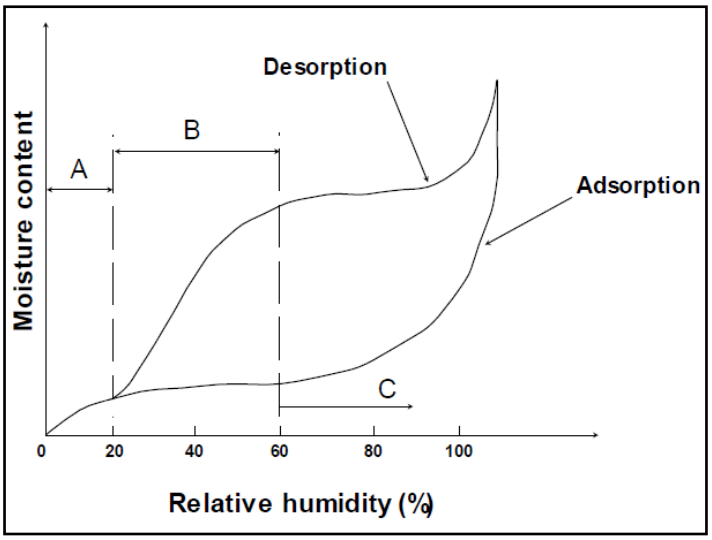


Figure 2.1 A typical moisture sorption isotherm for a food material (McMinn and Magee, 1999)

If a product is put under a set of humidity and temperature conditions, it will absorb or lose water from or to the ambient air, depending on the hygroscopic nature of the product. In Figure 2.1, the concept of hysteresis is illustrated where, food materials do not have identical curves in both adsorption and desorption cycles. According to Jangam and Mujumdar (2010), Sections A, B and C are unique zones that describe the water-binding characteristics within different areas in the solid matrix. They described Section A as an area where water is tightly bound, B as a region that water is less bound and C as a region that water is loosely held in the capillaries of the solid mass.

Water activity of food materials is indicative of the shelf-life and storability of moist food products. Jangam and Mujumdar (2010) described water activity as an important indicator for assessing the availability of water for the growth of microbes in food material, the germination of their spores and the participation of this water in a number of chemical reactions. They defined water activity as the ratio of the partial pressure of water over the wet food material to that of equilibrium vapour pressure of the water contained in the food material at a constant temperature and is mathematically expressed by equation 2.3.

$$a_w \quad \frac{P}{P_w} \quad \frac{R_{\ e}}{00} \qquad (2.\ )$$

where $a_w$ is the product water activity, P is the partial pressure of water in the food material $P_w$ the equilibrium vapour pressure and $RH_{eq}$ the equilibrium relative humidity.

Moisture sorption isotherms represent an equilibrium relationship between moisture content in food (Equilibrium moisture content, EMC) and $a_w$ (Shivhare *et al.*, 2004). Expressions of Equilibrium moisture content (EMC) models, with $a_w$ being one of its terms, have been described in literature. Some include Langmuir equation, Oswin equation, Halsey equation, modified Handerson equation and Chung-pfrost equation (Mwithiga, 2007). Jangam and Mujumdar (2010) gave the minimum water activity in foods for the growth and survival of different microorganisms as presented in Table 2.1.

Table 2.1 Minimum water activities for the survival of different microoganisms in food products (after Jangam and Mujumdar, 2010)

| Micro-organism | Water activity |
|---|---|
| Organisms producing slime on meat | 0.98 |
| *Pseudomonas, Bacillus cereus* spores | 0.97 |
| *B. subtilis, C. botulinum* spores | 0.95 |
| *C. botulinum, Salmonella* | 0.93 |
| Most bacteria | 0.91 |
| Most yeast | 0.88 |
| *Aspergillus niger* | 0.85 |
| Most molds | 0.80 |
| Halophilic bacteria | 0.75 |
| Xerophilic fungi | 0.65 |
| Osmophilic yeast | 0.62 |

The $a_w$ values in Table 2.1 imply that products stored in relative humidity environments that are lower than these values will not be conducive for the growth of the respective microorganism.

Water activity influences; the quality, safety, shelf-life, texture and flavour of food products. In most cases, controlling relative humidity is equivalent to controlling food spoilage (Jangam and Mujumdar, 2010). Temperature, for instance, varies water-binding characteristics, water dissociation, solubility of solutes or the condition of food matrix. Therefore, water activity is a function of food temperature and is product-specific (Jangam and Mujumdar, 2010). The measurement of water activity in different food products has been described by different authors (Prior, 1979; Slade *et al.*, 1991; Hamanaka *et al.*, 2006) . Nortjé *et al.* (2005) carried out proximate analysis of biltong during gamma irradiation. They

used water activity as one of the parameters used to measure the microbial safety of biltong using a Navosina Thermoconstanter TH-2 water activity meter at 25$^{o}$C. The water activity of the moist beef biltong was found to be 0.919. Yang *et al.* (2013) measured the water activity of dry roasted almonds using a CX-2 Aqua lab water activity meter. In their study, they found that water activity values of 0.2 to 0.3, produced almonds with maximum shelf-life.

The moisture ratio of food is a property that is dependent on the moisture content of a food sample. It is commonly used to characterize the drying kinetics of biological products. Yi *et al.* (2010) used a simplified version of the moisture ratio (MR) equation during the infrared drying of apple slices as presented by equation 2.4.

$$MR \quad \frac{M_t}{M_0} \qquad (2.\ )$$

where MR is the product moisture ratio (dimensionless), $M_t$ is the dry basis moisture content at drying time t, and $M_0$ is the initial moisture content expressed in dry basis.

Celma *et al.* (2009) calculated the moisture ratio equation during infrared drying of industrial wet grape residue using equation 2.5.

$$MR \quad \frac{M_t - M_e}{M_0 - M_e} \qquad (2.5)$$

where MR and $M_t$ are as defined earlier in equation 2.4 and $M_e$ is the dry basis equilibrium moisture content.

They, however, simplified equation 2.5 to equation 2.4, since it is widely described in literature as the MR equation which governs the infrared drying of biological products, where the equilibrium moisture content has a negligible effect on the MR (Toğrul, 2005; Shi *et al.*, 2008; Yi *et al.*, 2010; Khir *et al.*, 2011).

The drying rate ($D_R$) is described in literature as the amount of water removed from a product per unit time (Jangam and Mujumdar, 2010). It is calculated using equation 2.6 as suggested by Kaya *et al.* (2007).

$$D_R \quad \frac{M_t - M_{t\,\Delta t}}{\Delta t} \qquad (2.\ )$$

where $M_{t\ \Delta t}$ is the moisture content of the products after elapsed drying time, $\Delta t$. The variables, $M_t$ and $D_R$ are as defined earlier.

## 2.3 Food Drying Technologies

Food drying technologies continually evolve and range from convective drying methods to non-contact methods. A brief review of these technologies is discussed under the following subheadings.

### 2.3.1 Sun and solar drying

Sun drying is the oldest food preservation method available in which sunlight is used to dry food materials by spreading it (product) in layers on an open surface and exposing it to sunlight. Water from the food is lost through convective and conductive heat transfer. Natural sun drying comes with numerous challenges. Murthy (2009) summarized some of the shortcomings of sun drying of food materials as; failure of the product to dry uniformly due to varying sunlight, low drying rates and hence prolonged drying times that result in aflatoxin or microbial contamination, contamination by birds and debris brought by wind as well as insect infestation. Solar dryers are designed to eliminate or minimize some of the drawbacks attributed to sun drying. Solar drying therefore results in a remarkable improvement in the quality of the products.

The different configurations of existing solar dryers, as well as their classification, have been described in different sources. Green and Schwarz (2001) discussed, in detail, the various classifications of solar dryers, namely, direct solar dryers, indirect solar dryers, mixed mode solar dryers and hybrid solar dryers. Murthy (2009) classified commonly-used solar dryers in the Asian Pacific as natural convection cabinet types, forced convection indirect type and greenhouse solar dryers. The construction of these dryers, their common uses and possible alterations to make them more efficient have been discussed in detail by Murthy (2009).

Vega-Mercado *et al.* (2001) categorized dryers into four generations. They gave the first generation dryers as those that include cabinet and bed type that use heated air to dry the products. These dryers are suitable for drying food materials that are solid in nature. The second generation are those that are more suitable for dehydration of purees and slurries. They include spray and drum dryers and they can be used to produce dehydrated powders and flakes. The third generation dryers include freeze and vacuum dryers. These drying technologies are suitable in preventing structural changes that occur in food materials during drying thus affecting the food quality. The fourth generation dryers are technologies that are constituted by; high vacuum drying, fluidization, the use of microwaves, reflectance window

and radio frequency (RF). These methods are product-specific and they are used depending on the nature and the quality attributes of the end-product.

### 2.3.2 Freeze drying

Freeze drying technology is used primarily for drying and preservation of high value products. Vega-Mercado *et al.* (2001) described freeze drying as a drying technology used to overcome the structural changes that occur due to product shrinkage as well as overcome the challenges that can occur due to losses in aromatic compounds and flavour during drying. Ratti (2001) indicated that freeze drying is a method for dehydrating high-value food products (those that may be seasonal and perishable due to their limited availability, baby food that requires maintenance of maximum nutrient levels, nutraceutical foods, unique organoleptical foods such as aromatic herbs and spices or special high end foods such as those used in the military) where a sublimation-based dehydration method is used on a frozen product that adequately manages the microbial and enzymatic deterioration problems due to the low temperatures involved hence guaranteeing a high quality product. Generally, freeze drying involves high costs, making it prohibitive in its application. Freeze drying is often aided by a vacuum system.

### 2.3.3 Spray drying

Spray-dried products mainly constitute powders and flakes. Vega-Mercado *et al.* (2001) and Gharsallaoui *et al.* (2007) characterized spray drying technology as a drying technique that involves the atomization of food material as it is passed into the drying chamber as well as drying by spraying it continuously onto a hot drying medium. They described the advantages of spray drying as; (a) a technique that can be easily automated, (b) the resultant powder of the dried product is consistent in size, if the dryer conditions are held constant, and (c) a method that is versatile, with a wide range of equipment available.

### 2.3.4 Osmotic dehydration

Osmotic dehydration is described by Vega-Mercado *et al.* (2001) as a drying method in which water is removed from a food product by means of an osmotic gradient. It involves immersing a product in a hypertonic solution and water removal from the product is normally vacuum-aided.

Rastogi *et al.* (2002) discussed in detail the factors that the rate of water removal in osmotic dehydration depend on. They presented these as; the concentration of osmotic solution, its temperature, product size and geometry, agitation and magnitude of solution to dry matter.

### 2.3.5 Electromagnetic/non-contact technologies

Non-contact methods are drying technologies that do not use a heated medium as a means of heat transfer. The common technologies that fall under this category are the electromagnetic radiation sources such as microwave systems and infrared heaters. These systems have high energy efficiencies due to reduced heat losses. Vega-Mercado *et al.* (2001) described the mechanism of microwave heating as a process that takes place due to molecular and atomic polarization that occurs in the food mass when exposed to microwaves through the rotation of water molecules at high speed, in an effort to align with polarity changes in the present electromagnetic field. This rotation causes friction with the adjacent water molecules, resulting in heat energy generation that is governed by Equation 2.7.

$$P \quad . f \quad \left(\frac{E}{d}\right)^2 \quad \tan \quad 0^{\ 2} \tag{2.7}$$

where P is the heat generated in watts, f is the frequency of electromagnetic field, E the voltage, d the distance between electrodes, the product dielectric constant and tan the loss tangent.

Infrared radiation is also used as a heat source for drying food materials. This technology is the subject of this research and is discussed in detail in Section 2.4.

### 2.3.6 Emerging technologies

Drying technologies evolve through changes in the present food drying needs. Improvements in the existing technologies are also being made continually through research and product development (Pereira and Vicente, 2010; Vishwanathan *et al.*, 2013).

Emerging food drying technologies include; electro technologies, sonic assisted drying, superheated steam drying, heat pump assisted drying (Raghavan *et al.*, 2005) as well as ohmic heating (OH) (Goullieux and Pain, 2005; Pereira and Vicente, 2010). Electro technologies (Raghavan *et al.*, 2005) comprise of drying methods that use electromagnetic waves such as radio frequency (RF) and microwaves that heat up the food mass directly without heating the surrounding matter. These methods have huge energy savings (Geveke, 2005) and good prospects for industrial application. Heat pump assisted drying applies the

principles of refrigeration to cool and condense water out of air and is a method with very low operational costs compared to direct oil heaters, gas fired heaters or electrical heaters (Raghavan *et al.*, 2005; Hawlader *et al.*, 2006). Super-heated steam drying, uses super-heated steam to dry and remove water from food products (Raghavan *et al.*, 2005). Sonic assisted drying involves the use of low frequency sound (20-40 kHz) to dry products in combination with other drying methods such as hot air drying and has improved energy efficiencies when used with other drying methods (Raghavan *et al.*, 2005). Ohmic heating (OH) involves the passage of an alternating current through food products and by virtue of its electrical resistance; heat is internally generated within the food material (Pereira and Vicente, 2010).

### 2.3.7 Challenges of conventional drying methods

Conventional food drying technologies involve the use of hot air as the drying medium. Direct sun drying is a food drying method with huge limitations in its application as discussed in literature (Green and Schwarz, 2001; Murthy, 2009; Fudholi *et al.*, 2010). Solar drying depends heavily on the prevailing environmental conditions such as wind, rainfall and cloud cover and can often bring about product contamination and cannot be applied to drying of certain products such as cardamom (Murthy, 2009).

Fudholi *et al.* (2010) described some of the issues associated with open sun drying as follows: It is a drying technology that requires large open space, it is dependent on the amount of sunlight that is available and that the dried product is susceptible to contamination during drying.

Electrical systems that heat air by conduction and convection have also been widely used for the drying of different food products (Boughali *et al.*, 2009). Fuelled systems where a gaseous or liquid media is used to heat air for drying purposes have been used independently, or in conjunction with solar drying systems (Bhattacharya *et al.*, 2000). The reality is that these systems have low energy efficiencies among other problems such as the generation of waste heat and production of products of inferior quality due to heat damage as they depend on surface and volumetric heating (Murthy, 2009; Fudholi *et al.*, 2010).

With increased sense of health awareness by global food consumers (Pereira and Vicente, 2010), there is need to develop high quality foods that are affordable and leave a healthy ecological footprint in terms of the consumption of available natural resources and generation of minimum waste. Conventional drying systems constitute a huge chunk of industrial drying

applications as described earlier in this text. There is, therefore, a need for the development and application of other energy sources such as infrared that can be used to dry food products and other agricultural materials, giving products with improved food quality, and at the same time, protecting the environment (Raghavan *et al.*, 2005; Pereira and Vicente, 2010).

## 2.4 Infrared Drying

### 2.4.1 Introduction

Infrared radiation constitutes radiant energy that is part of electromagnetic spectrum and is the portion of the sun's energy that is important in heating objects on earth. It is generated by any object that is above the temperature of absolute zero degrees. Infrared drying utilizes this energy for drying food and other agricultural materials. Figure 2.2 depicts the electromagnetic spectrum and gives the approximate wavelength ranges for infrared radiation.

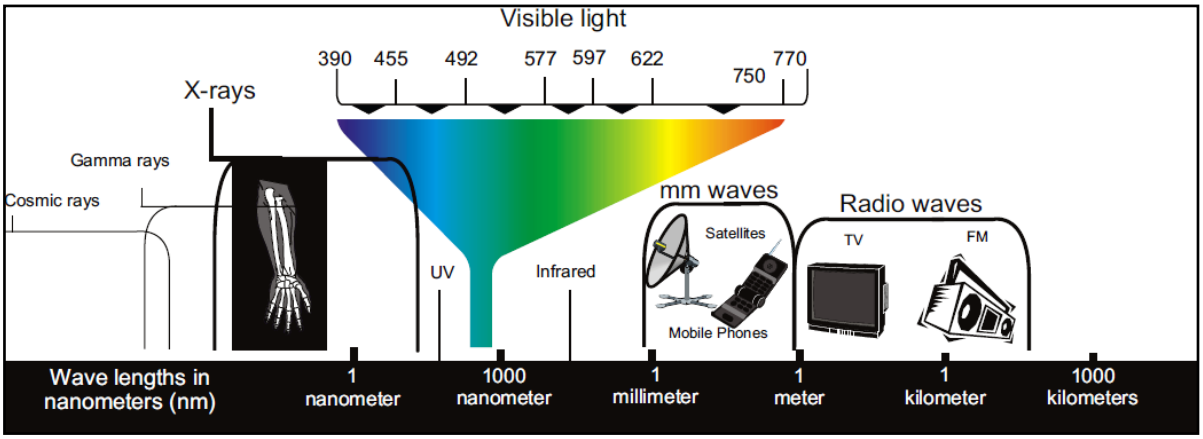


Figure 2.2 The electromagnetic wave spectrum (Jun *et al.*, 2011)

Infrared radiation for heating and drying applications in food processing is divided into three distinct regions depending on the emission wavelength range of the radiated energy (Jain and Pathare, 2004; Krishnamurthy *et al.*, 2008; Jun *et al.*, 2011; Rastogi, 2012). These regions are; the near infrared region (NIR) with a wavelength range of 0.75 to 1.4 µm, Middle infrared region (MIR) with a wavelength range of 1.4 to 3 µm and far infrared region (FIR) with wavelength ranges of 3 to 1000 µm (Sakai and Hanzawa, 1994). Infrared radiation, due to its physical nature, has spectral and directional dependence (Jun *et al.*, 2011). The importance of this phenomenon, is that, when infrared radiation is released from different sources, it comprises of fractions of different wavelengths, and this influences the fate of this

radiation when used for drying food products of different chemical compositions (Jun *et al.*, 2011).

Infrared heating has numerous applications in food processing and there are currently numerous research efforts made to understand the interaction of infrared radiation with different food materials. It is used in operations such as drying, dehydration, blanching, thawing, pasteurization, sterilization and other miscellaneous food processing operations such as roasting, frying, broiling, and cooking (Sakai and Hanzawa, 1994; Krishnamurthy *et al.*, 2008). The use of infrared radiation in enzymatic and microbial deactivation has also been widely discussed in literature (Shi *et al.*, 2008; Jihong *et al.*, 2010; Vishwanathan *et al.*, 2013).

### 2.4.2 Laws

There are laws that govern the propagation and absorption of infrared radiation by different materials. The wavelength in which maximum emission occurs for an infrared source is governed by the source's temperature (Krishnamurthy *et al.*, 2008; Jun *et al.*, 2011). This relationship is governed by the basic laws of black body radiation, including ien's Displacement Law, Planck's Law and Stefan-Boltzmann Law (Krishnamurthy *et al.*, 2008; Jun *et al.*, 2011).

Planck's law gives the spectral characteristics of radiation emitted by a black body that emits 100% of infrared radiation at a given temperature. Infrared radiation is produced by emitter sources (point sources) that are at different individual temperatures.

Max Plank in 1901 described the spectral black body emissive power distribution for a black surface surrounded by a transparent medium of refractive index n using equation 2.8.

$$E_b(T, \lambda) \quad \frac{2\ hC_0^{\ 2}}{n^2\ \lambda^5[e^{hC_0\ n\ kT\ \lambda} - \ ]} \qquad (2.\ )$$

where T the source temperature in K ($t^oC$ 27 ), h is Planck's constant given as . 2 x 0 $^{-34}$ J.s, n is the refractive index of the medium, the wavelength in μm, $C_0$ is the speed of light in km.s$^{-1}$ and k is Stefan-Boltzmann constant (1.3806 x 10$^{-23}$ J.K$^{-1}$).

A plot of equation 2.8 is shown in Figure 2.3.

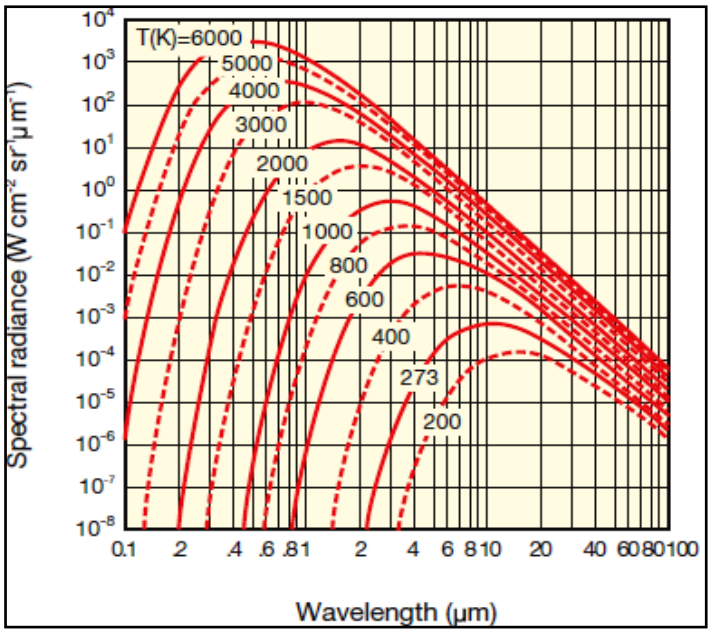


Figure 2.3 Black body emissive power spectrum (Hamatsu, 2010)

The emissive power increases with increasing temperature and the wavelengths of the corresponding maximum emissive power moves towards the shorter wavelengths. The total amount of infrared emissive power is calculated by integrating equation 2.8 for a given temperature range with respect to wavelength (Jun *et al.*, 2011).

ien's displacement law provides the wavelength that the spectral distribution of the radiation emitted by a black body gives maximum emissive power and is denoted as the peak wavelength. This law is as a result of differentiation of Planck's law which leads to equation 2.9 and 2.10 (Tsallis *et al.*, 1995; Jun *et al.*, 2011).

$$\frac{d}{d(n\ T)}\left(\frac{E_b}{n^{5}}\right) \quad 0 \qquad (2.\ )$$

$$_{max}\ \frac{2}{T} \qquad (2.\ 0\ )$$

where T is the emitter temperature in K (t°C 27 ) and $_{max}$ is the peak wavelength.

Stefan-Boltzmann law describes the total power radiated from an infrared source at a given temperature. The amount of this radiation is described by Sakai and Hanzawa (1994) as e uivale nt to the integration of the Plank's law as presented by equation 2.11.

$$E_b(T) \quad \int_0 E_b\ (T,\ )d \quad n^2T \int_0 \frac{C\ (n\ T)}{(n\ T)^5[e^{C_2\ (n\ T)} -\ ]} \quad n^2\ \ T \qquad (2.\ \ )$$

where $C_1$ 2h $C^2_0$, $C_2 = hC_0/k$ and i s Stefan-Boltzmann constant.

### 2.4.3 Mechanisms for infrared radiation absorption

The mechanisms for the absorption of infrared radiation when it impinges on food materials has been discussed by Krishnamurthy *et al.* (2008). They described food systems as complex mixtures of different biological polymers, salts, water and biological molecules with amino acids, peptides and proteins having strong absorption of infrared radiation at wavelengths of 3 to 4 µm and 6 to 9 µm, lipids having strong absorption of infrared radiation over the entire range of infrared band. However, it has stronger absorption with three localized bands of 3 to 4 µm, 6 µm and 6 to 9 µm. Figure 2.4 illustrates the infrared absorption bands of different food components in comparison to that of water.

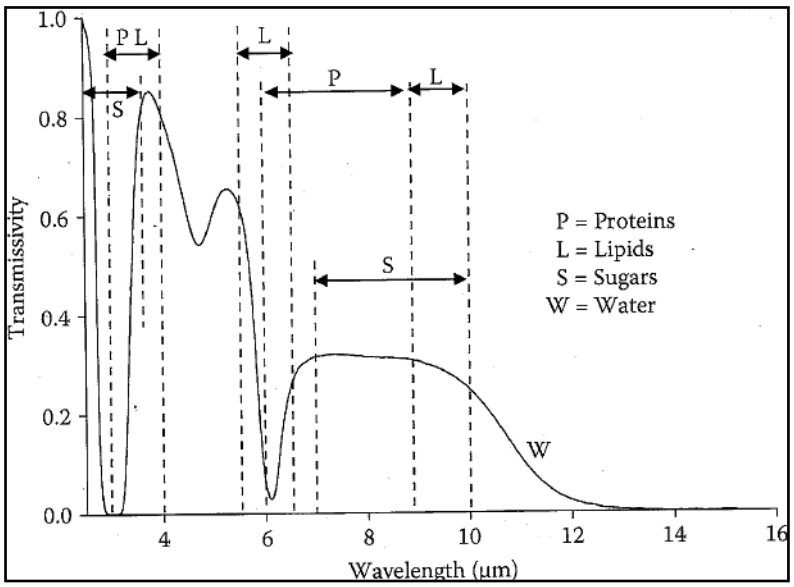


Figure 2.4 Infrared absorbtion bands for different food components compared to that of water (Jun *et al.*, 2011)

Decareau and Mudgett (1985) described the mechanisms for the interaction of infrared radiation with different materials. They indicated that infrared radiation causes heating up of food materials through;

(a) ionization as a result of changes in electronic state of molecules and ions in the material at wavelength ranges of 0.2 to 0.7 µm (ultra violet region),

(b) changes in the vibrational state of molecules and ions in the irradiated material that occurs at wavelengths of 2.5 to 1000 µm (FIR region), and

(c) changes in the rotational state of molecules and ions in the food material that occurs at wavelengths greater than 1000 μm (microwaves region).

It is generally understood that efficient absorption of infrared radiation takes place at FIR bands and the subsequent heating up of biological materials occurs through changes in their vibrational state (Krishnamurthy *et al.*, 2008).

### 2.4.4 Benefits of infrared drying

The infrared drying of food and other biological materials has numerous benefits that have been elaborated in the literature by different authors. Hamanaka *et al.* (2006) discussed in detail the effect of infrared heating on microbial populations. They indicated that the bonding conditions of water inside bacterial spores change considerably when infrared radiation is applied on a food material, affecting their development and survival. They also indicated that infrared heating targets the water characteristics in a food mass and it does not alter nutritive, chemical or important quality characteristics of the food if properly applied. Pan *et al.* (2008) studied the infrared drying of rough rice and found out that infrared drying had high drying rates and energy efficiency when dried in thin layers. Tanaka *et al.* (2007) and Pan *et al.* (2008) also reported that infrared drying can achieve simultaneous objectives of drying and disinfecting food materials from insect infestation, microbial and enzymatic spoilage.

Yang *et al.* (2013) investigated the effect of sequential infrared and hot air (SIRHA) roasting on the shelf-life and the quality of roasted almonds. They concluded that SIRHA roasting gave roasted almonds, the quality of which is comparable to that of conventional hot air (HA) roasting, with significantly lower production costs. Krishnamurthy *et al.* (2008) reviewed infrared drying of food materials and indicated some of the important attributes of infrared drying that set it apart from other drying methods. They indicated that infrared drying is characterized by high thermal efficiency and fast heating rates or response times when compared to conventional drying methods.

Afzal *et al.* (1999) investigated the energy requirements and the quality of barley in far infrared and convective drying where they calculated and compared the energy requirements for convective and far infrared drying methods as well as the quality attributes of germination, physical appearance and bulk density of the two drying methods. They concluded that FIR drying gave considerably higher drying rates compared to convective drying. Far infrared dried barley also gave high quality barley that is comparable to that of

the convective drying methods with germination percentages of over 95%. The experiments also showed a general decrease in the total quality (based on the germination, physical appearance and bulk density) of barley with increasing radiation intensity at the far infrared region.

Basman and Yalcin (2011) used infrared systems to dry noodles at a temperatures ranging from 53$^{o}$C to 128$^{o}$C from a moisture content of 75% to 8.5%. They observed that the oven-dried samples (the control, that were dried at a temperature of 45$^{o}$C) took 22 hours to dry while infrared-dried noodles took short drying durations of between 17 minutes and 3.5 minutes for emitters with lowest (909 W) and highest power (1673 W), respectively. Infrared-dried noodles also had the shortest cooking time of 3.75 minutes for the 1673W heater compared to that of the control samples that had a cooking time of 7 minutes 30 seconds.

### 2.4.5 Modeling of infrared drying

Drying models are mathematical expressions that describe the heat and mass transfer relationship of the drying process of biological materials by establishing; a relationship between the heat and moisture exchange between the air and the dried material, the equilibrium relationship between the dried product and the air or the adsorption and desorption rates of heat and moisture transfer (Jayas *et al.*, 1991).

Modeling of a drying process involves simulating the drying process of a biological product by fitting empirical or theoretical models to experimental data to yield constants that are used to simulate and estimate different drying parameters outside those tested under the experimental drying conditions and are useful in designing and optimizing drying systems and processes.

Krishnamurthy *et al.* (2008) reviewed some of the research work carried out with regard to modeling of infrared drying of different biological materials. They concluded that modeling infrared drying is a research-intensive area with numerous publications. There are published articles that seek explanations on the moisture diffusion characteristics of food materials, drying thicknesses and heat transfer phenomena in the food products (Toğrul, 2005; Krishnamurthy *et al.*, 2008; Ponkham *et al.*, 2012). Studies to explain the radiation energy driving internal moisture migration have also been extensively covered in literature (Khir *et al.*, 2006; Pathare and Sharma, 2006; Krishnamurthy *et al.*, 2008; Jun *et al.*, 2011).

Shi *et al.* (2008) investigated the drying characteristics of blueberries by carrying out infrared drying of both fresh and sugar infused blueberries. They assayed and fitted the drying time and MR data from their experimental work to six commonly-used empirical drying models. The coefficient of determination ($R^2$), reduced chi s uar e ($\chi^2$) and root mean square error (RMSE) were used to evaluate the extent that the models fitted the experimental data. These statistical values are given by Equations 2.12 – 2.14.

$$R^2 \quad -\frac{\sum^{n}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{\sum^{n}\left(\overline{MR_{exp}} - MR_{pre,i}\right)^2} \qquad (2.2)$$

$$\chi^2 \quad \frac{\sum_{i}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N - n} \qquad (2.\ )$$

$$RMSE \quad \sqrt{\frac{\sum_{i}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N}} \qquad (2.\ )$$

where $MR_{exp,i}$ is the experimental moisture ratio, $MR_{pre,i}$ is the predicted moisture ratio, $\overline{MR_{exp}}$ is the average experimental moisture ratio, N is the number of observations and n is the number of drying constants.

They concluded from their analysis that out of the six models tested, the Page Model and modified Page Model fitted well to the experimental data.

Toğrul (2005) also modelled infrared drying behaviour of apple slices where they fitted ten empirical and semi-empirical equations to the experimental data. They concluded that the modified Page equation was the best in explaining the drying behaviour of apple slices by establishment of the relationship between the MR and drying time.

Sharma *et al.* (2005b) modelled the infrared thin layer drying behaviour of onion slices where drying was conducted at three infrared intensities and eight mathematical drying models fitted to the drying data. The Page Model best fitted the experimental data and could therefore be used to explain the infrared drying behaviour of onion slices in thin layers.

Khir *et al.* (2011) modelled moisture diffusivity of rough rice during infrared drying. They determined the activation energies and moisture diffusivity coefficients of rough rice with a product temperature of 60$^{o}$C for different bed thicknesses as 9.2 x $10^{-9}$ $m^2.s^{-1}$, 6.2 x $10^{-9}$ $m^2.s^{-1}$ and 4.6 x $10^{-9}$ $m^2.s^{-1}$ for single layer thickness, 5 mm, and 10 mm, respectively, and the

corresponding activation energies to be 265.2 kJ.mol$^{-1}$, 223.6 kJ.mol$^{-1}$ and 128 kJ.mol$^{-1}$, respectively.

Afzal and Abe (2000) modelled the moisture changes in barley during far infrared drying where experiments were carried out at three different infrared intensities and air velocities. They established that modified exponential model (MEM) best fitted the experimental data and could be used to model and simulate FIR drying of barley.

Jain and Pathare (2004) modelled the convective and infrared drying characteristics of onion slices by conducting experiments at three infrared intensities, three air inlet velocities and three drying air temperatures to yield 27 drying trials. Nine mathematical models were fitted to the data. The results were evaluated based on goodness of fit using $R^2$, $\chi^2$ and standard error (SE). A model for predicting the moisture ratio of the onion slices at different drying times was developed that had an $R^2$ value of 0. 5 a nd a $\chi^2$ value of 4.4 x $10^{-5}$.

Ponkham *et al.* (2012) modelled the combined FIR and hot air drying of pineapple slices with and without shrinkage. The samples were dried at air temperatures of 40-60$^{o}$C and infrared intensities of 1-5 kW.m$^{-2}$. Quality models were developed using total colour difference, shear force ratio and shrinkage where these variables were fitted to empirical models. The quadratic model predicted shrinkage more accurately, while quartic model was best at estimating the colour differences and the logarithmic and modified Midilli-Kucuk Models were best at estimating the shear force ratio.

Yi *et al.* (2010) investigated the drying kinetics of apple slices under simultaneous infrared dry blanching and dehydration (SIRDBD) with intermittent heating and then modelled the drying characteristics and the enzymatic inactivation in the product. The Page Model was fitted to the drying data due to its simplicity and performance in accurately predicting thin layer drying of fruits and vegetables.

Equation 2.4 that describes moisture ratio for infrared drying of biological products was also used to calculate the MR. The Page Model gave RMSE and $R^2$ values of 0.013 and 0.9932, respectively, and therefore could adequately represent the drying behaviour of apple slices under SIRDBD. The effective moisture diffusivity was determined in the same study by plotting the MR against the processing time in a log scale, based on Equation 2.15.

$$\text{In(MR)} \quad \text{In}\left(\frac{M}{M_0}\right) \quad \text{In}\left(\frac{}{2}\right) - \left[ \ 2\frac{D_{\text{eff}}t}{2}\right] \qquad (2.5)$$

where H is the slice thickness in m, t is the drying time in seconds and $D_{eff}$ is the effective moisture diffusivity in $m^2.s^{-1}$.

The activation energy of the drying process was determined from the slope of the curve where the effective moisture diffusivities were plotted against absolute surface temperatures, based on the simplified Arrhenius equation (2.16).

$$D_{eff} \quad D_0 \exp\left(-\frac{E_a}{RT_s}\right) \qquad (2. \ )$$

where $D_0$ is the reaction coefficient, $E_a$ the activation energy in $kJ.mol^{-1}$, R is universal gas constant in $kJ.mol^{-1}.K^{-1}$ and $T_s$ the target surface temperature ($T^oC+273$) K.

### 2.4.6 Infrared drying and product quality

The quality of dried food and agricultural materials often influence customer acceptability and is dependent on the product in question. Studies on the effects of infrared drying on different products have been carried out and discussed in literature. Basman and Yalcin (2011) studied the quality changes during infrared drying of noodles. They observed that infrared-dried noodles developed bubbles in the product interior, giving the final product distorted shapes due to the rapid moisture loss from the products. Higher infrared intensities gave lower cooking losses. This was attributed to the partial coagulation of gluten structure in the product. Infrared-dried noodles, however, gave a significantly lower total organic matter (TOM) content and lower swelling volumes, indicating inferior product quality. It was concluded that the 1673W emitter gave better quality with lowest cooking loss and TOM values compared to the other heaters ranging from 273W to 1782 W.

The study by Sebastian *et al.* (2005), where drying of meat was carried out using radiant plates, drying temperatures of 30 to 60$^o$C were reported in the products. The drying process in this study produced products with acceptable benzo(a)pyrene deposition due to the application of the concept of the separation of heating gases.

Infrared systems can also be used to achieve microbial decontamination of meat products. Huang (2004) observed that Frankfurters reached an average surface temperature of over 70$^o$C after 103.2 seconds, when two 1000 W infrared ceramic heaters were used to heat the products. The process reduced the *L. Monocytogenes* on the Frankfurters by an average of 3.5±0.4 Logs to 4.5±0.2 Logs when the surface temperature was raised to between 70 to 80$^o$C.

Yi *et al.* (2010) investigated the quality characteristics of apple slices under SIRDBD and intermittent heating. The study investigated three processing parameters that relate to the product quality. These are product surface temperature, slice thickness and processing time. They conducted a three-factor experimental design to investigate the effects of these parameters on the drying characteristics of apple slices and the final quality (indicated by slice surface colour, moisture reduction, peroxidase (POD) and poly phenol oxidase (PPO) activities). They established that thin apple slices heated up faster than thicker ones and thicker slices had a higher average core temperature. Thin slices also gave lower PPO activities with slice thickness having a higher impact on inactivation of PPO than the processing temperature. POD showed similar inactivation characteristics to those of PPO. The study also concluded that drying of apples at a temperature of 75$^{o}$C gave a reasonable processing time and the least total colour difference ($\Delta E$) of 2.27 for samples that were processed under SIRDBD.

Vishwanathan *et al.* (2013) investigated the effects of infrared blanching and infrared assisted hot air drying on the quality of carrot slices. The quality characteristics of processed carrots under these systems were compared to those processed using conventional blanching and drying methods. Enzyme inactivation level, retention of Vitamin C and rehydration characteristics of the products were used as an indicator of the product quality. The effect of sample thickness on inactivation of POD was also investigated. Thinner slices (5 mm) blanched faster than thicker (10 mm) slices that took 10 minutes and 15 minutes, respectively. The study showed that Vitamin C retention by infrared blanched samples was significantly higher than that of conventional methods. The study also showed that infrared blanching took a longer time compared to the conventional blanching methods but it was recommended due to its higher nutrient retention. The rehydration capacity of infrared blanched samples was approximately 5% higher than that of conventionally blanched and dried samples. This was attributed to the uniform heating of infrared drying and the resultant absence of case hardening.

Jihong *et al.* (2010) investigated some of the quality changes during infrared drying and pasteurization of almonds. Sensory attributes were tested by a panel of 90 untrained panellists. SIRHA roasted as well as HA roasted almonds were tested in terms of their texture, flavour, appearance and overall quality. Colour changes after the two treatments were also measured. Recommendations for the medium roast based on the industry standards were

given for infrared roasted almonds in terms of the infrared intensity, roasting time and temperature based on the colour changes. The sensory quality for both infrared roasted almonds and HA roasted almonds showed no significant difference based on a two-way analysis of variance (ANOVA) data analysis.

### 2.4.7 Infrared drying and food safety

The presence of contaminants in food materials of a different nature and various origins greatly affects their food safety. Of an important consequence is the occurrence, of high microbial levels and spoilage-causing enzymes during food handling and processing operations. Infrared drying is able to achieve both drying and inactivation of microbial elements as well as elimination of enzymatic spoilage (Tanaka *et al.*, 2007; Vishwanathan *et al.*, 2013).

Tanaka *et al.* (2007) investigated FIR heating as an alternative decontamination method of strawberries using FIR heaters of different power intensities and configurations. It was recommended that heating be from four orthogonal directions towards the food sample in order to achieve higher decontamination levels, uniform heating and less damage to the strawberries. It was also concluded that further investigations on the cyclic heating should be done in order to assess further possibilities of FIR decontamination of strawberries.

Hamanaka *et al.* (2006) investigated the effect of infrared emitter wavelength on decontamination of bacterial spores. In their study, they concluded that the inactivation of these spores is dependent upon the water activity of the product and the peak wavelength of the emitter. This implied that an infrared heater with an appropriate peak emission wavelength has to be selected for a given water activity level.

The microbial load in meats and other food products is an important indicator of its level of contamination, and may also be used to evaluate the effectiveness of the processing operations. Thermal treatments, among other hurdles, are important in reducing the microbial load in food products. Drying is one of the most important hurdles that not only thermally destroys microbial populations, but also reduces the amount of available water for microbial reactions (Rao, 1997).

Nortjé *et al.* (2005) studied the effect of gamma irradiation on the sensory quality of biltong and observed that conventionally-dried biltong did not achieve the recommended food safety requirement of 5.0 log reduction of microbial populations (USDA, 2012). The use of gamma

radiation at a level of 4 kGy to 8 kGy achieved this requirement without adversely affecting the sensory quality of biltong. They therefore recommended a maximum gamma radiation dose of 4 kGy since it resulted in the best sensory quality scores. Infrared heating from the latter discussion, can be used achieve microbial reduction in biltong and guarantee microbial safety to its consumers.

## 2.5 Methods of Quality Analysis

Drying of food products affects their quality, and drying methods that minimize quality changes in food processing should be developed and adopted. There are numerous quality parameters that can be used as indicators of quality for different products and these have been widely discussed in literature. The methods for their analysis have also been documented. Some of these methods have been widely accepted in the food processing industry as standards. The important quality parameters considered during a drying process will depend on the nature of the product being dried and its end use. The main quality indicators assessed during food processing include nutrient changes (proteins and vitamins), acceptability (colour, flavour and texture) and safety (microbial load, browning, rancidity etc.).

### 2.5.1 Colour

The colour of food products is considered an important quality parameter that is influenced by the chemical, microbial, biochemical and physical state of a product after its production, postharvest handling and processing. Colour in itself is an indirect method for the measurement of food's ua lity. The methods of food colour measurement are instrumental (objective) and visual (subjective) (Pathare *et al.*, 2013).

Pathare *et al.* (2013) and MacDougall (2002) described colour as an attribute measured with reference to several coordinate systems. Some of the most popular colour coordinate systems are given as,

(a) RGB (Red, Blue, Green colour system- commonly used in colour video monitors)
(b) Hunter L a b
(c) CIE L*a*b*
(d) CIE XYZ
(e) CIE L*u*V
(f) CIE Yxy
(g) CIE LCH

Figure 4.1 presents an illustration of the CIE L* a* b* coordinate system that was developed as an improvement of the Hunter Lab system in 1975.

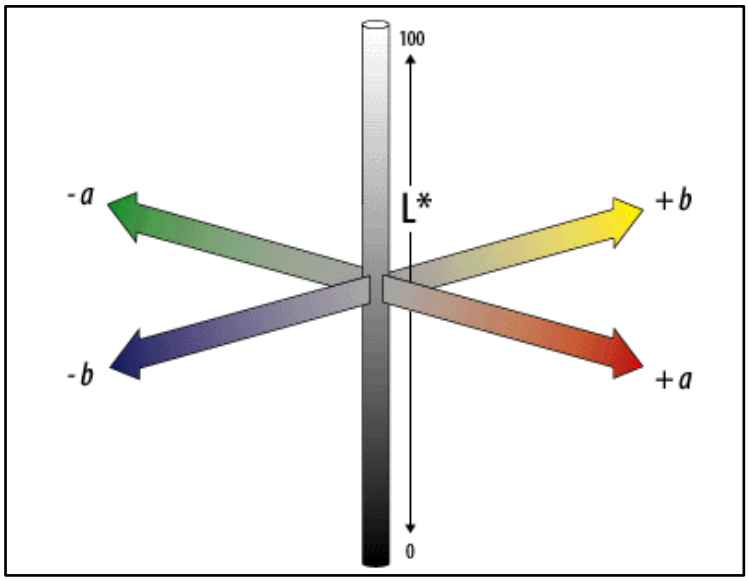


Figure 2.5 The CIE L*a*b* colour space showing the different colour parameters relative to each other (after Pathare *et al.*, 2013)

Pathare *et al.* (2013) and MacDougall (2002) indicated that colour quantification is commonly given based on the HunterLab and CIELAB scales. These two scales are widely used in the food processing industry (Carpenter *et al.*, 2001; MacDougall, 2002; Pathare *et al.*, 2013). In the CIELAB colour space, a* and b* are the colour coordinates and L* is an index of lightness and they are all read directly from their respective colour spaces. The a* colour parameter takes positive values for reddish colours and negative values for greenish colours while the b* colour parameter takes positive values for yellowish colours and negative values for bluish colours. The L* value estimates the luminosity or the lightness with values ranging from 0 to 100 (MacDougall, 2002) while a* and b* values range from -60 to +60.

Chroma (C*) is described as the quantitative measurement of colourfulness given by the equation 2.17. The higher the chroma values, the higher the colour intensity as perceived by the human eye.

$$C^* \quad \sqrt{a^{*2} \quad b^{*2}} \qquad (2.\ 7)$$

The hue angle (h*) is given by equation 2.18 and higher hue values represent less yellowness, with hue angles of $0^o$ or $360^o$ = Red hue, $90^o$ = Yellow hue, $180^o$ = Green hue and $270^o$ = Blue hue.

$$h^* \quad \tan\left(\frac{b^*}{a^*}\right) \qquad (2.\ \ )$$

The total colour difference ($\Delta E$) indicates the u antitative changes during a processing step and can be used as a measure of the quality changes that have occurred in a product after processing. It is presented in form of equation 2.19.

$$\Delta E \quad \sqrt{\Delta a^{*2} \ \Delta b^{*2} \ \Delta L^{*^2}} \qquad (2.\ \ )$$

The whiteness index (WI) gives the overall whiteness of food materials and can show the level of discolouration during a drying process which is important in predicting heat damage. It is presented by equation 2.20.

$$I \ \sqrt{(00 \ -L^{*2}) \ a^{*2} \ b^{*2}} \qquad (2.20)$$

Colorimeters are the basic instruments used for the measurement of the colour of food products in the food processing industry. The other instrument system used is the computer vision measurement system where product images are captured using either a charge coupled device (CCD) camera, ultrasound, magnetic resonance imaging (MRI) or computed tomography (CT). Subsequent steps taken after image acquisition consist of image pre-processing, image processing and subsequent analysis based on industry colour space models. Hue intensity saturation schemes (HIS) system commonly gives good results in this respect (Pathare *et al.*, 2013).

### 2.5.2 Textural characteristics

Textural properties of food are important quality attributes that indicate their level of maturity and their ability to meet handling, packaging and processing requirements. Chen and Opara (2013) described food texture as "all the rheological and structural (geometric and surface) attributes of a product perceptible by means of mechanical, tactile and where appropriate visual and auditory receptors". They indicated that the textural properties of foods are measurable by means of descriptive sensory (subjective) analysis and instrumental (objective) analysis. Subjective methods mainly constitute the use of a sensory test panel that evaluates

the textural properties of food materials. The number of people that make up sensory panels as well as the methodologies adopted may vary, and the panel may be trained or untrained. Sensory panels often use a sensory scale and have numerous limitations that instrumental methods are designed to eliminate. Instrumental methods are classified into destructive and non-destructive methods. Some of the destructive methods include three-point bending test, single-edge notched bend (SENB) test, compression test, puncture test, and imitative methods (Bourne, 2002; Chen and Opara, 2013). Some of the non-destructive methods include ultrasonic methods, mechanical methods and optical techniques with a wide range of instruments being used for both destructive and non-destructive methods (Bourne, 2002).

### 2.5.3 Rehydration characteristics

Rehydration of dried food materials measures the structural changes that have occurred in the food matrix after a single or multiple processing steps. Lewicki (1998) described rehydration as a measure of the magnitude of injuries inflicted on food products during a drying process and other handling operations prior to rehydration. Rehydration tests can be carried out using different procedures of measurement as well as rehydration times ranging from 2 minutes to 24 hours. Different formulae for the measurement of rehydration are presented and three are shown in Equations 2.21 – 2.23 (Lewicki, 1998; Maskan, 2001a).

$$\text{Rehydration ratio} \quad \frac{\text{eight after rehydration}}{\text{Mass of dry matter}} \tag{2.2 }$$

$$\text{Rehydration capacity} \quad \frac{\text{eight of water absorbed during rehydration}}{\text{eight of dry matter}} \tag{2.22}$$

$$\text{ater absorption capacity (} \quad \text{AC)} \quad \frac{\text{Mass of water absorbed during rehydration}}{\text{Mass of water removed during drying}} \tag{2.2 }$$

Maskan (2001a) investigated the rehydration, shrinkage and drying characteristics of Kiwi fruits under different drying methods. They compared the rehydration characteristics of kiwi fruits dried under microwave, conventional HA method and combined microwave and HA systems. Rehydration of the samples was done after the completion of the drying processes where the samples were weighed and immersed in hot water at 50$^{o}$C for 50 minutes. The samples were re-weighed after every 10 minutes by removing them quickly from the water for not more than 30 seconds. The rehydration capacity, also described as percentage of water gain, was calculated using equation 2.24.

$$\text{eight gain } (\quad) \quad \left(\frac{t - d}{d}\right) 00 \qquad (2.2)$$

where $W_t$ is the rehydrated weight after time t and $W_d$ the initial weight before rehydration.

It was noted that samples that had fast rehydration capacity had good quality. Combined microwave and HA dried samples gave higher rehydration capacities and low shrinkages compared to the other drying methods thus indicating better quality.

### 2.5.4 Shrinkage

Shrinkage constitutes a reduction in size when a food product undergoes a processing operation. Food materials commonly shrink after drying, indicating physical and chemical change within their structure. Mayor and Sereno (2004) reviewed the effects of drying on the shrinkage properties of food products. They indicated that cracking of dried products is as a result of non-uniform shrinkage and it reduces the rehydration capacity of food materials. They defined shrinkage as "relative or reduced dimensional change of volume, area or thickness". Equation 2.25 mathematically expresses the bulk shrinkage of biological products as presented by Mayor and Sereno (2004).

$$S_b \quad \frac{V}{V_0} \qquad (2.25)$$

Where $S_b$ is the bulk shrinkage, V is the final volume and $V_0$ the initial volume of the product. $S_b$ values range from 0 to 1.

Bacelos and Almeida (2011) studied the shrinkage of blanched and dried spherical potato samples with a radius of 10 mm. They recorded the weight and size changes during drying using computer vision and weighing system and fitted the data into shrinkage models. Both the Linear and Kilpaltrick Models gave a good account of the shrinkage process.

Yan *et al.* (2008) investigated different methods used for the measurement of shrinkage of banana, mango and pineapple samples after drying. Four methods were proposed and used to conduct shrinkage experiments for these products after drying. The true shrinkage values were thereafter measured using a gas pycnometer. The Archimedes Principle method, using n-heptane, gave a lower coefficient of variation indicating better accuracy compared to the solvent displacement, glass beads displacement and liquid pycnometry methods.

## 2.6 Historical Background and Importance of Meat Drying

The forthcoming discussion highlights the historical perspectives of meat drying where details of its invention and importance to early civilizations are presented. A review of the important ancient and current dried meat products by different communities across the world is given and culminates in the detailed description of biltong and the challenges facing its production: this being the product of interest in this study.

### 2.6.1 Historical background

Drying of meat is one of the first important technological inventions of primitive man. Three primary modes of meat preservation were originally developed, that consisted of drying, refrigeration and salting (Wentworth, 1956). Improvements on these methods continually emerged as man evolved. This was necessitated by the unique circumstances that prevailed in his environment. Tools such as spicing and smoking aided these original preservation technologies (Wentworth, 1956). Spicing and smoking imparted special flavours on the meat products that made them taste better, thus improving palatability, lengthening their shelf-life and generally yielding products of improved quality.

Drying was discovered by early man merely through his instincts for survival. Through trial and error and experience, man discovered that dried meat could be kept for a long time in the ambient environment without spoilage. The chemical, microbial and enzymatic changes that occurred during drying were not immediately understood as the mechanisms that extended the shelf-life of dried meats (Zeuthen, 2008).This came about as meat leftovers on carcasses that were left out in the open hot environment dried quickly, after the hunters killed the animal and consumed the raw meat. Hunting communities of pre-historic man gradually learned and adopted meat drying as a means of keeping surplus food for rainy days. The preservation of meat in this way evened out fluctuations as a result of its seasonal availability. This shifted man's ability for survival from mere chance to an assured state. Meat drying also improved food availability in prehistoric times for the communities, rapidly increasing numbers that concentrated in camps (Zeuthen, 2008). Man's diet also diversified from being predominantly vegetarian due to inclusion of animal protein in his diet (Isaac, 1971). The discovery of drying of meat occurred in pre-historic times and the actual point in time cannot be verified as no record of such exists (Justin, 2012).

A combination of meat preservation technologies are often used together, drying being one of the most important ones. Fermented meats are often prepared by the creation of an environment in meat products that favours the growth of specific micro-flora resulting in chemical changes that extends the shelf-life of the products. Drying is required before the actual fermentation processes commences (Campbell-Platt, 1995).

The anthropological evidence for the origin of meat drying points to Africa or Asia (Wentworth, 1956). Meat drying gradually spread from different parts of the world as prehistoric man traded with his neighbours or migrated to areas with better climate, food and away from disasters and calamities such as diseases, drought and other harsh natural occurrences (Justin, 2012). Meat drying spread to the Americas approximately forty to sixty centuries ago (Wentworth, 1956). Man's lifestyle changed due to the discovery of meat preservation by drying. Global exploration and trade with other communities became the norm due to the portability of dried meat ration that could be carried over large distances (Wentworth, 1956). The unavailability of wheeled transportation required dried meat to bear minimum loads that could easily be packed and transported by travellers on foot (Wentworth, 1956), yet be shelf-stable under local environmental conditions. Travellers' numbers along prehistoric trade routes swelled gradually, bringing about the concentration of communities and the building up of centres that supplied food and other trading merchandise to travellers.

Jerky was a premium trading product, with high demand along the trading highways (Wentworth, 1956). Wentworth (1956) indicated that dehydration of meat in the western hemisphere became a common practice from the Arctic Circle to Patagonia, with different Brazilian tribes in South America using smoking as a meat preservation tool. Portuguese explorers called dried meat xarque; the English called it Jerky, Spanish explorers called it char-qui and the Mexicans called it tasajo. Northern American natives also called it Jerky while the Canadian region called it Pemmican (Wentworth, 1956). There were variations in the composition of these products as well as the production processes involved but the basic process used was drying and with the meat source, commonly from herbivores, being the primary raw material.

Anthropological studies have shown that the caribou was the main meat source for the diets of the Arctic and sub-Arctic natives, although the North Eastern regions relied on the muskoxen and salmon in areas of San Francisco. The Central American region depended on the bison that, to date, produces the best flavoured Jerky under conditions of wind and sun

drying (Wentworth, 1956). New England and Eastern Canada produced dried meat primarily from the deer and moose and occasionally used meat from the elk (Wentworth, 1956).

Pemmican seldom required the addition of fat to improve its palatability as it already contained 30 to 35 fat when dry. Generally, dried meat improved early man's nutrition this being the prime source of protein in his diet. There were, however, challenges with regard to its sensory characteristics with many of its consumers claiming that it did not taste right (Wentworth, 1956). Other consumers claimed that dried meat products had a fishy flavour. The cause of this phenomenon was not immediately understood although early civilizations thought this occurrence to be a result of poor handling. This was later understood to be caused by rancidity of fat components in the dried meat products. High dependence on meat as the sole source of food by explorers often brought about nutritional deficiency problems. Scurvy was the biggest and most severe nutritional deficiency that led to the death of many travellers and explorers who consumed dried meat on their voyages, without any other food sources (Wentworth, 1956).

### 2.6.2 Dried meat products

Different communities around the world still practice meat preservation by using various approaches. Drying is the predominant meat preservation process practiced by a majority of communities and individuals with different pre-treatment and drying methods being used. Generally, processed meat products are classified into four major groups depending on the pre-treatment and the drying methods used to process and preserve them. Table 5.1 presents the four classes of processed meat products.

Table 2.2 Categories of processed meat products (after Vandendriessche, 2008)

| **Treatment** | **Whole Muscle** | **Grounded Products** |
|---|---|---|
| Heat treated | I = Cooked ham | III= Luncheon meat (e.g. beef Jerky) |
| Non-heat treated | III= Dry cured ham (e.g. Iberico ham) | IV= Fermented sausages (e.g. Chorizo) |

Heat treated meat products are dried or cooked at temperatures exceeding 50$^{o}$C while non-heat treated meats are dried at temperatures lower than 50$^{o}$C and have no visual evidence of

heat damage (Vandendriessche, 2008). Meat products may also undergo salt or spice treatment before the drying process or be dried "fresh".

The following sub-sections briefly describe some of the dried meat products consumed by different communities around the world.

**Pemmican**

Pemmican is a nutritionally complete dried meat product originally prepared by the Canadian people (Wentworth, 1956). It is currently eaten by communities in the Northern American plains (Rooker, 2013). Pemmican is prepared from lean buffalo (bison) meat that is dried during the summer months and thereafter, rendered fat is added in order to preserve and store it as the primary ration during winter (Rooker, 2013). The lean bison meat is dried at temperatures below 49$^{o}$C, followed by the addition of fat that is heated at temperatures above 94$^{o}$C to remove water and release fat from its cellular structure (Rooker, 2013). Pemmican was stored in sealed animal hides filled with rendered fat and kept away from moisture, heat and direct sunlight (Wentworth, 1956; Rooker, 2013). This mode of storage made it last for many years as a shelf-stable (SS) product without any other additional preservation measures or cold storage (Rooker, 2013). Variations of traditionally prepared pemmican exist as prepared by different communities. Sweet pemmican was prepared by the Northern American Indians by addition of marrow fat to the dried meat. Ordinary pemmican, on the other hand, was produced from bison hump fat added to dried buffalo meat (Wentworth, 1956). Generally, pemmican contains as low as 35% fat to a high of 80% fat (Wentworth, 1956; Rooker, 2013). Fat rancidity was the main problem associated with the production, processing and storage of pemmican. Other communities added dried berries to pemmican. However, this practice seemed to worsen the storage problems and consequently reduced the shelf-life of these products (Rooker, 2013). Pemmican is consumed with fat to improve its palatability, enhance texture, product flavour and improve its nutrition.

**Charque**

Charque is common in Brazil and other South American countries and consists of large flat pieces of beef not more than 5 cm thick preserved by salting in brine and drying (FAO, 2013a). This product is prepared from beef hind- or fore-quarters that is cut into thin strips then marinated for about an hour in brine (FAO, 2013b). The brine is then allowed to drain into the brine tank by laying the meat slabs on flat slats, before drying commences (FAO,

2013b). Charque is commonly sun dried for four to six hours in a span of four to five days at temperatures not exceeding 40$^{o}$C and in an environment that is protected from wind and rain (FAO, 2013b; FAO, 2013a). After drying, the meat is packed in jute sacks for storage and distribution (FAO, 2013b). It can also be packaged in retail-size vacuum packs to improve shelf-life and appearance (FAO, 2013a). Charque is often consumed by de-salting, by cutting it into small pieces and cooking it with other foods, such as beans, rice or foods such as "feisao" which are commonly consumed in the South American region (FAO, 2013a).

**Pastirma**

Pastirma is a dried meat product consumed by the Turkish, Egyptian or Armenian people made by salting and drying beef from older animals or camel meat (Temell , 20 ; FAO, 2013b). Meat cuts from hindquarters is sliced into long strips of 50 to 60 cm and a maximum diameter of 5 cm (FAO, 2013b). Salt is rubbed into the meat with aid of incisions made on the surface to improve its penetration (FAO, 2013b). Drying is carried out at ambient conditions for 2 to 3 days during the summer and 15 to 20 days during winter (FAO, 2013b). Pastirma is covered with a paste, commonly called "cemen", after drying and salting. Cemen is made up of spices, paprika, mustard and water (FAO, 2013b). The paste covers the product for a day and thereafter, it is dried at room temperature for 5-12 days (FAO, 2013b). After this process, the product is ready for sale or consumption. Pastirma has a better microbial and shelf-life compared to other RTE meat products such as biltong (FAO, 2013b). The product is a RTE snack and is consumed raw, in a manner similar to biltong (FAO, 2013c).

**Odka**

Odka is a product prepared by drying lean beef cut into large pieces and it is dry salted then sun-dried (FAO, 2013b). Sun drying takes 4 to 6 hours and thereafter the meat is cut into smaller pieces and cooked in oil (FAO, 2013b). Sauces and spices are added to the cooked product and drying is thereafter allowed to continue to completion (FAO, 2013c). After the final drying process, odka is stored in tight containers that contain oil for a stable shelf-life of about one year (FAO, 2013b). Okda is a product that is predominantly prepared and consumed by the Somali community of East Africa (Mapesa *et al.*, 2010; FAO, 2013b).

**Qwanta**

Qwanta is a dried meat product prepared from lean beef that is cut into strips of 20 to 40 cm in length and hung over wire in the kitchen to dry for a period of 24-36 hours (FAO, 2013b).

Before drying, the slices are coated with a sauce made up of 50% hot pepper, 25% salt and 25% aromatic seasoning (FAO, 2013b). After drying, light smoking may be carried out followed by frying in fat, and then further drying is done to complete the process (FAO, 2013b). After these processes, qwanta is ready for storage and consumption (FAO, 2013b). Qwanta is commonly consumed in Ethiopia and other East African countries (Temell , 20 ; FAO, 2013b).

**Kilishi**

It is a dried meat product prepared from lean beef, goat meat or lamb during the hot months and dry weather in semi-arid zones of Nigeria and other semi-arid zones of West Africa (Mapesa *et al.*, 2010; Temell , 20 ; FAO, 2013b). Some industries produce kilishi in large scale for commercial purposes where it is tray-dried in warm oven air after slicing the meat into strips of 0.5 cm thick, 15 cm in length and 6 cm wide (FAO, 2013b). Traditionally, the meat strips were spread on raised papyrus mats for sun drying (FAO, 2013c). Hygiene problems associated with papyrus mats necessitated the use of raised wire platforms for sun drying (FAO, 2013b). Sun drying takes place in stages, with the first stage having products' moisture content reduced by 40% to 50% (FAO, 2013b). The product is then marinated in an infusion consisting of groundnut cake paste and spices, causing it to increase its weight by up to three times (FAO, 2013b). After the marinating process, sun drying is carried out again for about three hours to a moisture content of 20 to 30% and lightly roasted in glowing fire to impart special flavours to the product (FAO, 2013b). Kilishi can be roasted or not roasted, with the roasted type having superior flavour (FAO, 2013b). After roasting, the product has its moisture content reduced to about 10 to 12% (FAO, 2013b). With proper packaging (hermetic sealing in low-density plastic bags), the product remains shelf-stable for about one year (FAO, 2013b).

**Sirken**

This is a dried meat product prepared by dry-salting lean beef or goat meat that has been cut into slices of about 15 to 30 cm long, 3 to 6 cm wide and 0.5 to 3 cm thick. The pre-treated product is dried in the kitchen by hanging it under the roof over the kitchen fire. Sirken is traditionally prepared in order to safely store excess meat from slaughtered animals for long periods of time in areas with no cold storage. When the product is dry, it has a shelf-life of several months without any packaging. The product is consumed by the Kalenjin community and other neighbouring communities in Kenya.

**Jerky**

The word Jerky comes from a Spanish word ‘char ue ’ that means dried meat (Thiagarajan, 2008). Jerky is commonly referred to as the ‘iron ration’ of the Northern American people (FAO, 2013c). The processing technology for jerky production varies from industry to industry and household to household as there is no universal approach to its production (FAO, 2013c). Traditionally, Jerky is prepared by slicing whole meat into long, thin slices that are thereafter dried (Thiagarajan, 2008). These strips should be approximately 0.5 cm thick, 1-2 cm wide and 15-20 cm long (FAO, 2013c). Jerky is a shelf-stable meat product that is popular among hikers, bikers, hunters and skiers (Thiagarajan *et al.*, 2006). Jerky can either be dried whole from lean meat or prepared from ground meat. Jerky also depends on drying, and salting or spicing for its shelf stability (Thiagarajan *et al.*, 2006). It can be prepared from buffalo (bison) meat, antelope, beef, turkey or deer (FAO, 2013c). After slicing or grinding, it can be dried using different drying methods. In some instances, smoking is done to impart distinct flavours on the product. Jerky is commonly stored after drying or consumed as a RTE snack.

**Biltong**

Biltong is a meat-based snack widely consumed in South Africa and is commonly described in the country as a national delicacy. Lewis *et al.* (1957) described the origin of the word ‘biltong’ and its preparation. They indicated that the word biltong is made up of two parts, ‘*bil*’ referring to the hind ua rters of an animal and ‘*tong*’ which means a fillet. It is a product that has been in existence for centuries in the republic of South Africa and has been commonly-used by nomads and trekkers. Biltong is also consumed to a limited extent in other countries, in the entire southern Africa region (FAO, 2013b). There are different recipes for the preparation of biltong, some of which are custom-designed depending on the individual consumer preferences.

Biltong is generally prepared from meat products of freshly killed herbivores by cutting the loin region lengthwise in lengths varying from 1 to 2 feet and strips 2 inches wide (Lewis *et al.*, 1957; Nortjé *et al.*, 2005). The strips are then salted using coarse salt (1-2 kg for every 50kg of meat) and spiced with ingredients such as pepper, garlic, sugar, coriander or aniseed to meet the taste preferences of consumers (FAO, 2013b). The strips are then dried by hanging in ambient air under a shade to protect it from rain, frost or dew. The dried biltong is then ready for storage or consumption after 10-14 days of drying.

Nortjé *et al.* (2005) prepared biltong for their experiments using 300-350 g beef strips purchased from a commercial biltong producer, Gull foods. They salted and marinated the strips for 12 hours in a sodium chloride-based solution and hung them for 48 hours in air with temperatures of 28-32$^{o}$C and relative humidity of 70%. In the study, the chemical composition of moist beef biltong is presented in Table 2.3.

Table 2.3 Chemical and intrinsic properties of moist beef biltong (after Nortjé *et al.*, 2005)

| Parameter | Mean value (±standard deviation) |
|---|---|
| Moisture content (%) | 46.7 (±1.27) |
| Protein content (% wb) | 45.2 (±1.19) |
| Crude fat content (% wb) | 1.53 (±0.09) |
| Ash content (% wb) | 5.65 (±0.17) |
| NaCl content (% wb) | 3.70 (±0.18) |
| NaCl in moisture content (%) | 7.94 (±0.67) |
| $a_w$ | 0.919 (±0.008) |
| PH | 5.53 (±0.05) |

## 2.7 Discussion and Conclusion

Infrared drying technology is an immensely active research area as a drying method with numerous benefits when successfully applied to drying of different food products. Infrared drying as discussed in preceding chapters, can confer a host of benefits to ready-to-eat (RTE) meat products such as biltong, a product that is the subject of study in this research. Biltong can benefit from infrared drying, particularly from a microbiological safety and quality standpoint.

There are currently no published articles on infrared drying of biltong. The effects of different spicing methods, drying methods as well as product sizes on quality attributes of biltong have not been investigated. These factors are important in designing optimized processes that yield high quality products.

In combined infrared and convective drying, the effects of drying parameters, particularly the air velocity and the relative humidity should be investigated in order to establish the point at which there is highest energy efficiency. Models that describe the infrared drying for biltong, have also not currently been investigated and developed. In addition, there is the need to study the storage stability of dry biltong in order to establish the critical parameters that can significantly extend its shelf-life. This study, therefore, intends to address some of the research gaps highlighted above.

# 3. MATERIALS AND METHODS

## 3.1 Sample Preparation

The beef carcasses that were used to make the samples used in this study were acquired from a local butchery (Pick and Pay, Pietermaritzburg), twenty four hours prior to the commencement of drying experiments. The samples were prepared from the loin region of the carcass. The cuts were made 1–2 cm from the carcass's surface to ensure that the samples were of relatively uniform moisture content, as 1–2 cm of the outer layer of a slaughtered carcass normally loses moisture and is of relatively lower moisture content than the inner region (Trujillo *et al.*, 2003).

The cuts were immediately sliced along the muscle fibres (Dzimba *et al.*, 2007) to lengths of 15 cm, widths of 2.5 cm and to thicknesses of either 1.5 cm, 1 cm or 0.5 cm, using a commercial meat slicer (Model 610, Hobart Corp., Troy, OH, USA). The samples were then packed in low density polythene bags that were heat sealed using a commercial heat sealer (Kenpak Heat Sealable, Fisher Scientific, USA) to limit moisture loss during transportation to the laboratory, which was done within 30 minutes after packaging. The samples were then stored in the laboratory at a temperature of 4$^{o}$C before the commencement of the marinating process that was done within 2 hours after the samples reached the laboratory.

The marinade was first prepared by mixing warm water and spices in proportion, to give a salt concentration of 14%. This marinade concentration is recommended for making biltong (FAO, 2013b) that, therefore, required 140 g of spice (Nice and spicy, Home of biltong makers, Gauteng, South Africa) mixed with 860 g of warm water to give the required marinade concentration of 14% w/w. The ingredients of this spice are, a flavouring agent (celery, antioxidant, monosodium glutamate), spices, sucrose, salt and preservative (sodium sorbate–E202). The marinade was prepared in two litre food grade containers (Basic plastics, Pietermaritzburg, South Africa) and was thoroughly mixed by agitation using a food hand blender (HR1680, Philips, UK) for two minutes and left to stand in a refrigeration unit for one hour at 4$^{o}$C to allow its temperature to stabilize (C385, Defy appliances pty., South Africa). Two containers with marinade were prepared per drying run.

Before marinating the fresh-sliced samples, their moisture content was determined in triplicate from three random samples using the AOAC 950.46 standard method (AOAC, 2003) where the samples were rapidly ground using a meat grinder (FP120, Kenwood, UK),

thoroughly mixed and passed through a 3 mm sieve. Three covered aluminium dishes of approximately in 80 mm diameter and 25 mm in depth were each filled with 12 grams of ground samples. The samples were dried in a forced-air mechanical oven (prolab, PRIS, South Africa) for 16 hours at a temperature of 102$^{o}$C. The samples were then cooled in a desiccator and thereafter weighed using an Adam Core balance. The moisture content of the marinated samples was also determined using the same method after each marinating process.

Twelve samples consisting of batches of four samples, each with a thickness of 5 mm, 10 mm or 15 mm with the other dimensions remaining the same, were put in each of the two containers holding the marinade. The samples were individually placed in the marinade maintained at 4$^{o}$C, in a way that each sample was completely immersed in the marinade and did not touch the adjacent sample in order to ensure that each sample had osmotically equal capacity to marinate. The samples were marinated for a period of 6 hours and later the same was replicated for periods of twelve hours and twenty four hours. Each of the containers holding the marinade and the samples were labelled with a unique code to identify the marinating duration as well as when the marinating process started and when it ended.

The L* a* b* colour values of the raw and marinated meat samples were measured in three replications using a Hunter lab colorimeter (Colourflex EZ, Hunterlab, USA). The volume of samples of each thickness and marinating duration was measured using Archimedes method, where water was used as the displacement liquid as described by Thiagarajan (2008). This was done prior to the start of each drying run in triplicate. Excess water from the surface of these samples was removed using blotting paper.

### 3.2 Experimental Design

The experiment was arranged in a Randomized Complete Block Design (RCBD) with three drying conditions (blocks); convective air system (60% RH and 25$^{o}$C), 2.5 µm peak infrared heater (set at an intensity of 4777 W.m$^{-2}$) and 3.5 µm peak infrared heater (set at an intensity of 4777 W.m$^{-2}$), three biltong slice thicknesses (5, 10 and 15 mm) and three marinating treatments (6-, 12- and 24-hour marinating durations) with three replications. Eighty-one drying runs were, therefore, conducted under this treatment structure, which is illustrated in Figure 3.1.

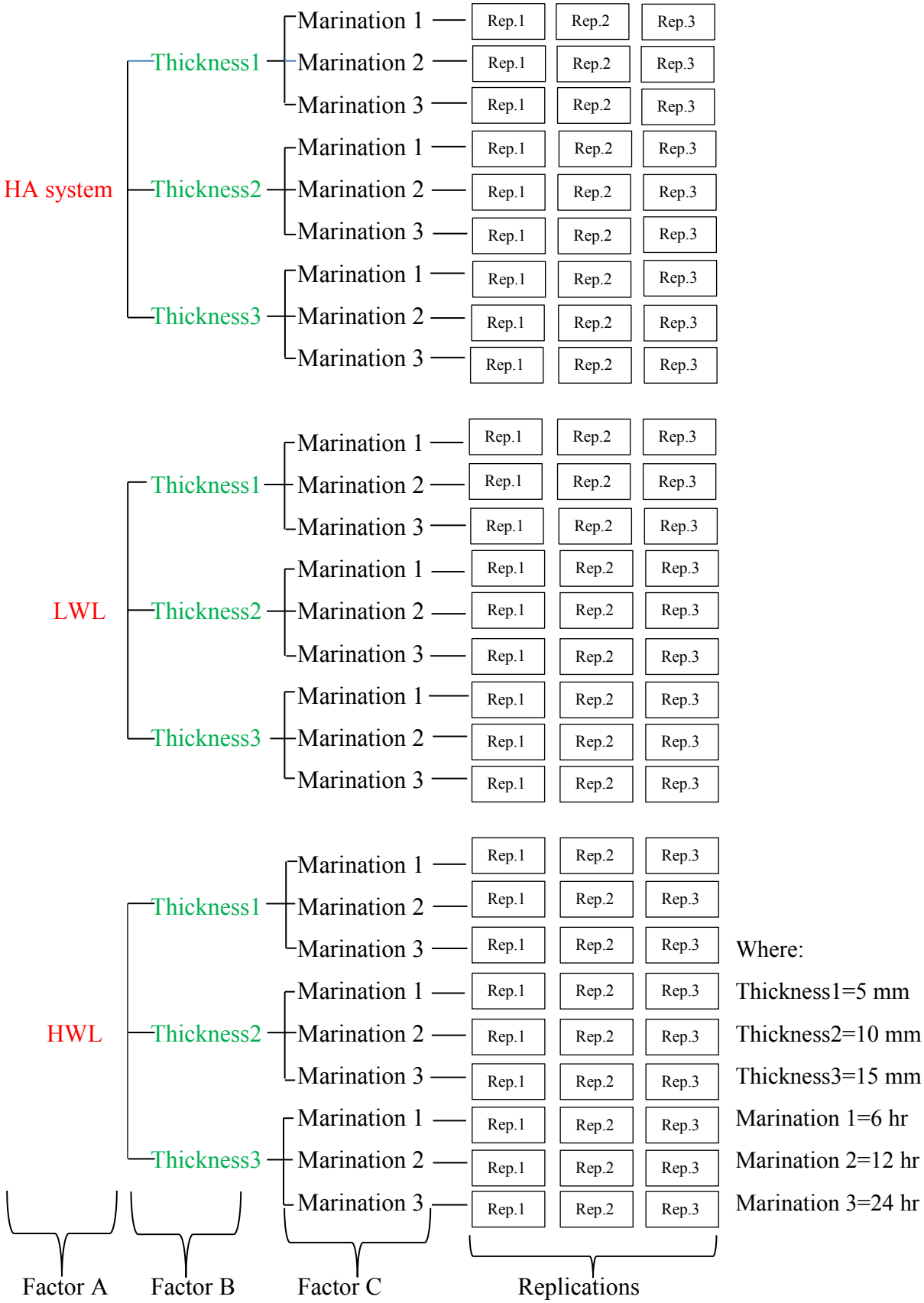


Figure 3.1 Schematic presentation of experimental treatment structure with three factors (factor A= Drying conditions, factor B= Slice thicknesses and factor C= marinating treatments) and three replications

## 3.3 Drying Experiments

Three drying methods were investigated in this research namely; convective air drying and infrared drying using two infrared heaters with 2.5 μm and 3.5 μm peak wavelengths, but both heaters set at an infrared intensity of 4777 $W.m^{-2}$ at the product surface. In total, three drying treatments were evaluated.

### 3.3.1 Conventional drying

**Drying equipment**

Convective air drying was carried out in a forced-air mechanical oven (prolab, PRIS, South Africa). The oven is 0.95 m x 0.65 m x 0.77 m (LxWxH) in size. It is connected to a 220VAC outlet and has a temperature control unit with a resolution of 0.1$^{o}$C and an accuracy of ±0.5$^{o}$C. Its operating temperature range is 0$^{o}$C to 220$^{o}$C.

**Hot air drying procedure**

Drying runs were conducted in a forced-air mechanical oven (prolab, PRIS, South Africa) at an air temperature of 25$^{o}$C and approximately 60% RH. The drying unit controller maintained the e uipm ent's interior temperature at an accuracy of ±0.5$^{o}$C from its set point temperature. The dryer was run idle for two hours prior to drying in order to stabilize it.

A drying run involved placing 6-hour marinated samples in the convective dryer. These were comprised of 3 pieces of 5 mm thickness, 3 pieces of 10 mm thickness and 3 pieces of 15 mm thickness. Three drying runs were carried out for each sample group marinated for a different length of time.

The weight loss of each sample was monitored at regular intervals by quickly removing the sample from the drying unit, weighing it and putting it back in the dryer (within 10 seconds). The door of the drying unit was closed after removing the sample to limit temperature fluctuations in its interior. Weighing was done using an electric balance (CQT 202, Adam Core, USA). The samples were removed from the drying unit when they reached the target moisture level of 20% ± 1% wb and stored in labelled ziplock polythene bags (Victoria packaging, Pietermaritzburg, South Africa) in order to prevent water adsorption or desorption, prior to the quality analysis tests. This moisture content was determined based on preliminary investigations of the moisture level of commercial biltong found in different retail outlets.

Each sample was put in its ziplock bag and stored at room temperature. Quality analysis tests were carried out for each drying run immediately after all the samples reached the target moisture level.

### 3.3.2 Infrared drying

**Heater characteristics**

Two infrared heaters were used to investigate the effects of different infrared peak emission characteristics on the drying kinetics of biltong. Model QF-121210 (Omega, UK) had a surface temperature of 538$^{o}$C at the peak emission wavelength of 3.5 µm while model QC-121240 (Omega, UK) had a surface temperature of 871$^{o}$C at the peak emission wavelength of 2.5 µm. The heaters had aluminized steel casings for maximum strength, mounting studs and equal dimensions. The heaters also had similar response times of 7–8 minutes. Model QF-121210 had an emitting surface made of black quartz ceramic cloth surface with an output wavelength range of 2.5 to 6 microns while model QC-121240 had an emitting face made of high purity fused quartz glass with an output wavelength range of 2.5 to 6 microns. The infrared spectral characteristics and response times for the heaters are shown in Figures 3.2–3.5.

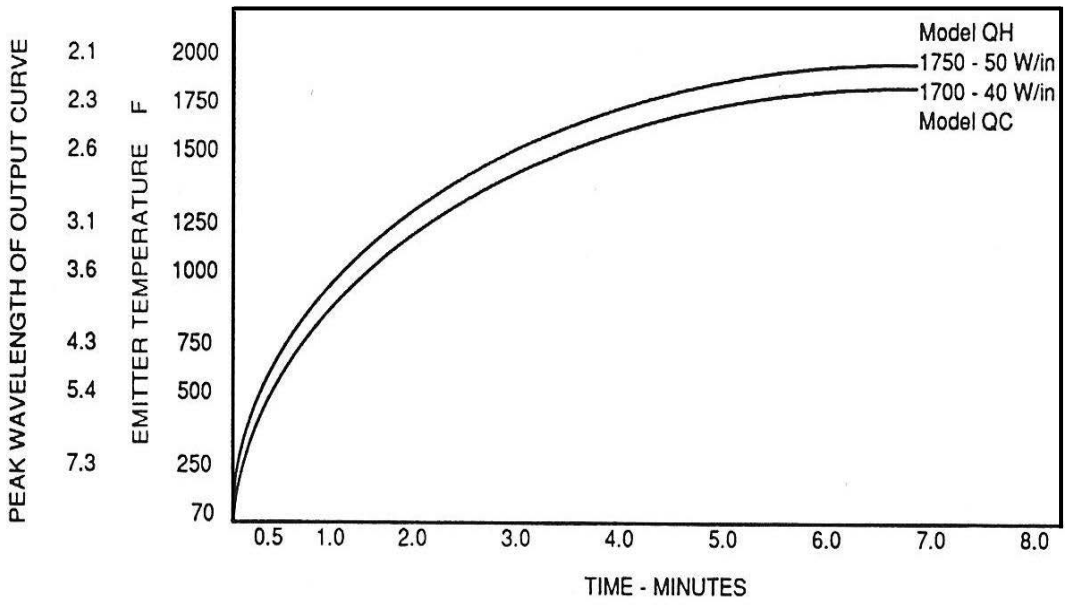


Figure 3.2 The response time of model QC-121240 (Low wavelength-LWL) infrared heater (Omega, 2013)

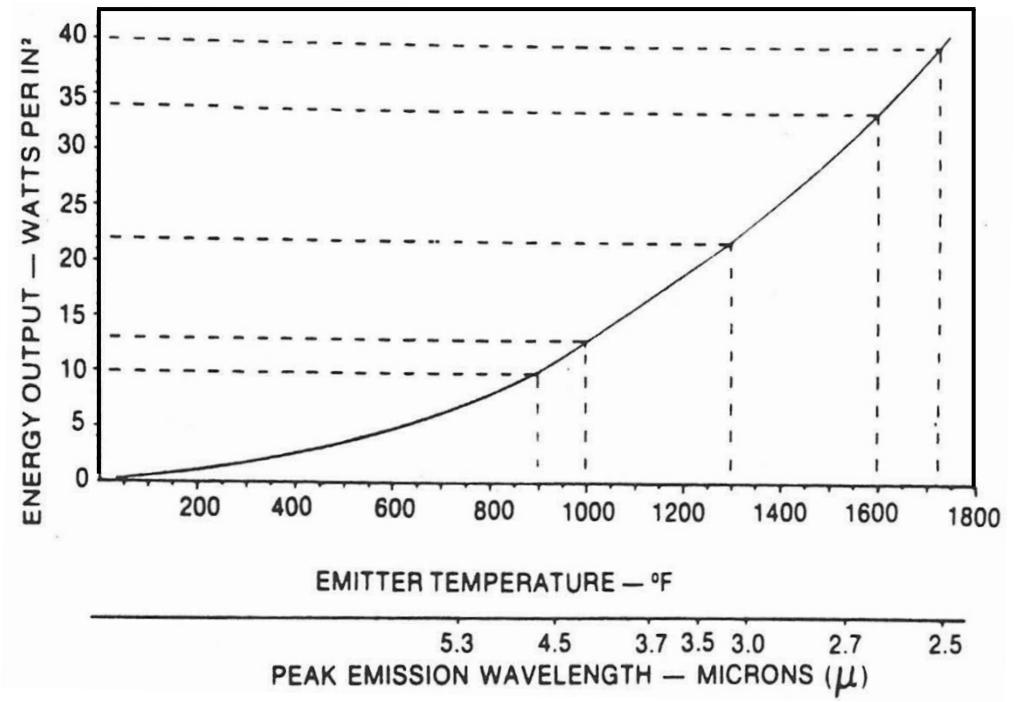


Figure 3.3 The emission characteristics of model QC-121240 (Low wavelength-LWL) infrared heater (Omega, 2013)

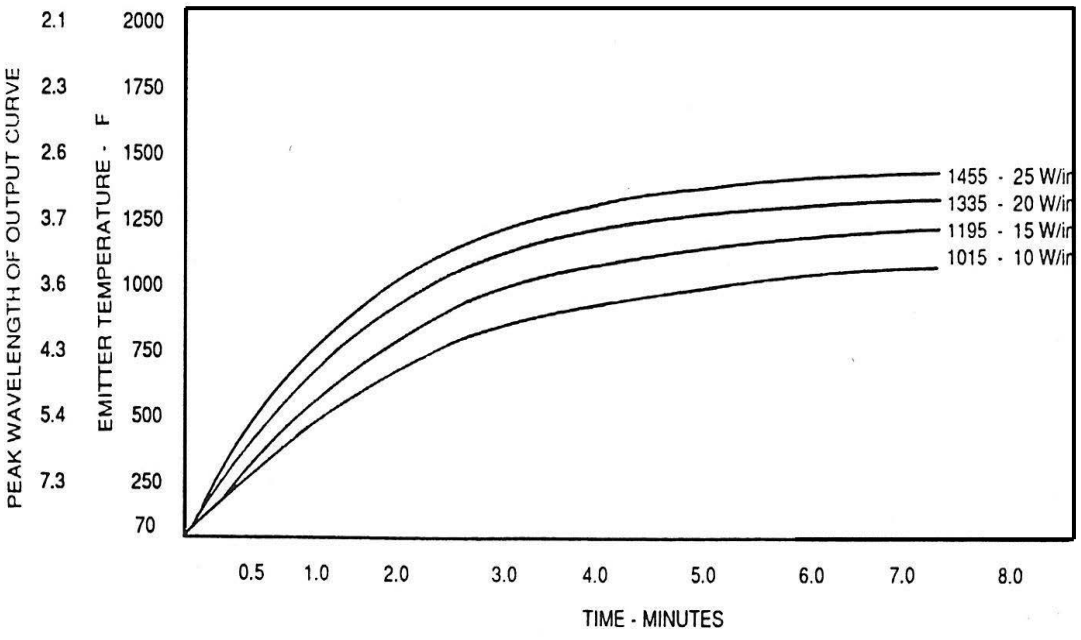


Figure 3.4 The response time of model QF-121210 (High wavelength-HWL) infrared heater (Omega, 2013)

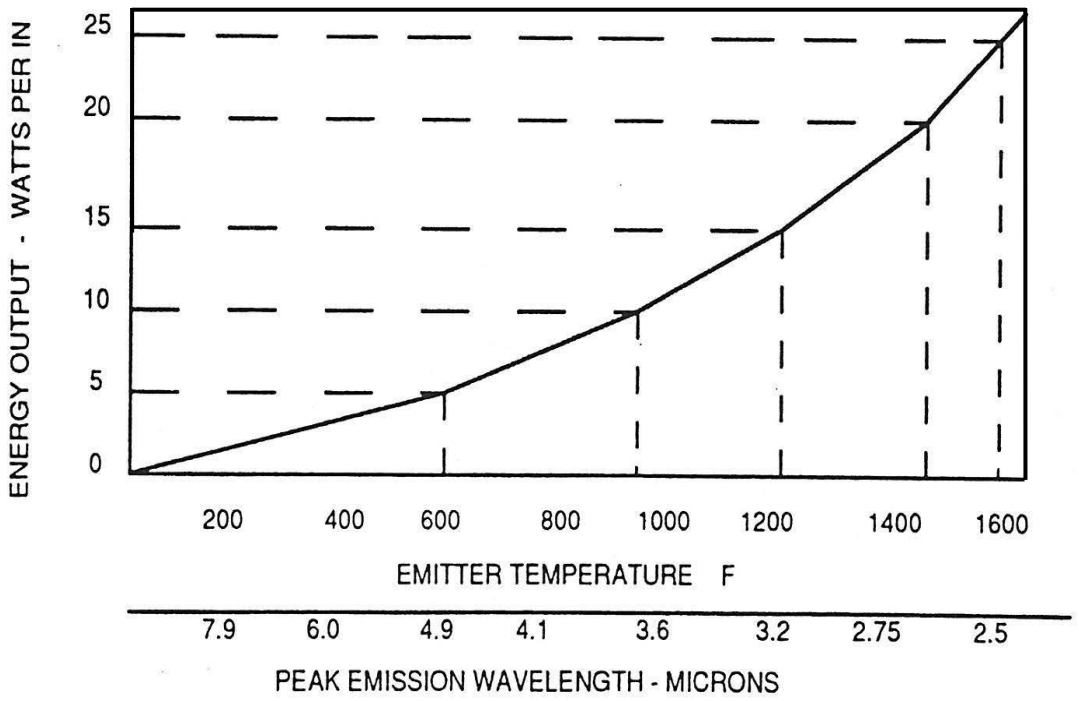


Figure 3.5 The emission characteristics of model QF-121210 (High wavelength-HWL) infrared heater (Omega, 2013)

The heaters were connected to 220V AC outlet with the QF-121210 model (High wavelength infrared heater-HWL) drawing 1440 Watts while the QC-121240 (Low wavelength infrared heater-LWL) model drew 5760 Watts on a dual voltage connection.

**Description of experimental infrared drying system**

Figure 3.6 presents a sketch of the infrared drying rig with the infrared heater mounted on it. The heaters shared a drying rig designed to accommodate one infrared heater (Part A in Figure 3.6) at a time. The drying tray (E) was made of food grade stainless steel wire grill mounted on a vertically sliding frame for height adjustment (D). The heaters were mounted at the top of the rig on a mounting frame with the radiating surface facing downward (B). The drying rig was open on its four sides, to allow free convective air movement over the products.

The heater's electrical outlet was first connected to a power meter (DEM0 5S G, Acorp, South Africa) that recorded the power used in kWh by each heater for each drying run. The low wavelength infrared heater (LWL) used 2.5 mm electrical leads, while the high wavelength infrared heater (HWL) used 1.5mm electrical leads

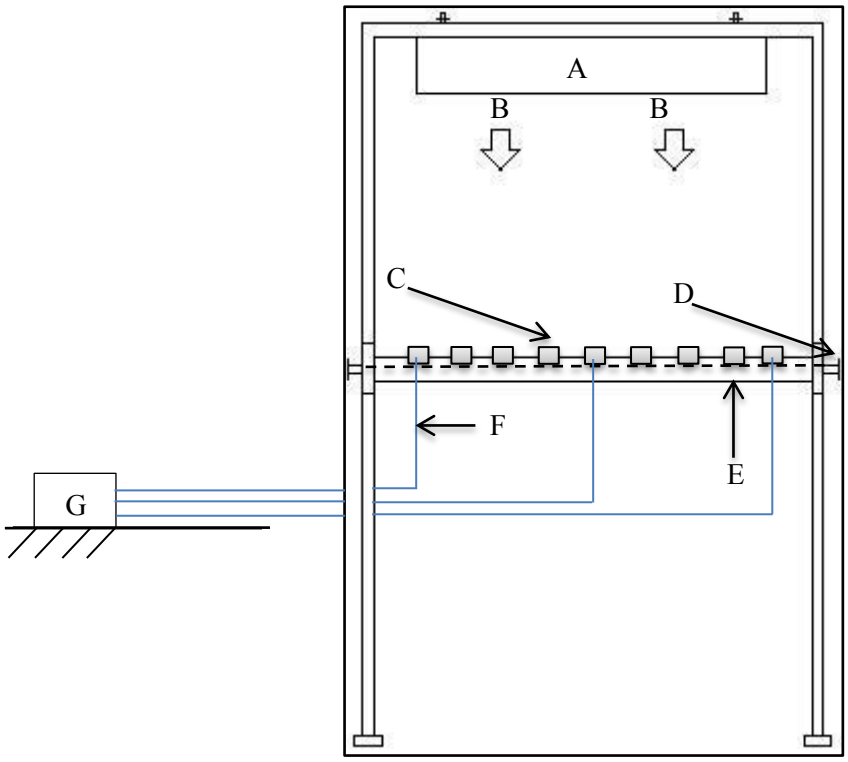


Figure 3.6 A sketch of the assembled infrared drying rig depicting the relative positions of the infrared heater (A), the radiating surface (B), thermocouple (F) placement in biltong sample (C) that is placed on a vertically adjustable (D) drying tray (E) , and the data logger (G) connected to the thermocouples

**Infrared drying procedure**

Each drying run used the same protocol as that of convective air dried samples. Samples were put in the drying tray 8 minutes after switching on the heaters to ensure that drying occurred at the heater's maximum temperature. Each of the samples had its temperature monitored by a K-type thermocouple (TC-TT-KI-24, Omega, UK) placed at the approximate centre of the samples (illustrated by Part F in Figure 3.6). The thermocouples were connected to a data logger (OM-DAQ-USB-2401, Omega, UK), (part G in Figure 3.6) that automatically recorded the product temperature at its approximate centre point every 30 minutes as shown. Samples were placed on the drying tray in a way that they covered up the entire surface without touching the adjacent sample, for maximum interception of the radiation from the heaters. The drying tray was also set perpendicular to the radiating heater surface and had the same surface area as the heaters (0.3 by 0.3 m). Moisture loss for each of the samples was monitored at suitable intervals in the same manner as for samples dried under the convective air dryer. The drying process was terminated when the sample reached the target moisture level of 20% ± 1% wb. They were then removed from the dryer and each of them stored in a

labelled Ziploc bag, waiting for quality analysis tests that commenced immediately after they cooled down to room temperature. This process was repeated for each of the three marinating levels, and for each heater, after separately setting the infrared intensity of each heater to 4777 $W.m^{-2}$ at the product surface by adjusting the distance between the drying platform and the radiating surface. An infrared power meter (LS122, Shenzhen Lishang Technology Co. Ltd, China) was used to achieve this. This intensity of 4777 $W.m^{-2}$ was selected based on preliminary tests carried out on the heaters and information gathered from literature (Krishnamurthy *et al.*, 2008; Jun *et al.*, 2011).

## 3.4 Quality Analysis

### 3.4.1 Colour

The product colour was measured at three stages during the processing of fresh product, the marinated product and the dried product, using a Hunterlab colorimeter (Colourflex EZ, Hunterlab, USA),only one with an instrument port size of 60 mm and an aperture size of 31.5 mm (1.26 inches). The instrument was standardized at start-up, using black and white standardization tiles.

The samples were prepared according to the American Meat Science Association (AMSA) guidelines (AMSA, 2012), where a sample was cut into three slabs; 2.5 by 2.5 cm and allowed to bloom for 5 minutes. Each slab was then placed in a transparent glass cup, which was positioned on the instrument port in such a way that the sample fully covered the instrument port. A black cup was then placed over the glass cup with the sample in it, in order to cover it so as to ensure that no light escaped from the instrument when readings were taken. The L* a* b* values were measured using Illuminant A at an observation angle of $10^{o}$ as recommended by the AMSA (AMSA, 2012). For each sample, readings were made for each of the three slabs with readings being repeated three times for each slab.

### 3.4.2 Texture

**Puncture test**

The peak puncture force for dry the samples was measured using an Instron Textural Analyser (Model 3345, Instron Corp., Canton, MA) with a load cell capacity of 5 kN and a cylindrical probe with a diameter of 3.1 mm. Peak puncture force measurement for each sample was repeated three times at a cross head speed of 0.5 mm/sec. This was done on a sample by changing the puncture points in a way that the sample (rectangular slab), was

divided into three equal parts by marking then the approximate centres of the three parts used as puncture points. The peak puncture force that was required for the probe to completely pierce through the product was recorded by the system's Bluehill 2® software (Instron Corp., Canton, MA). Characteristic force-deformation curves were also plotted using the automatic Bluehill 2® software already installed in the online computer.

**Texture profile analysis (TPA)**

Texture profile measurements were carried out using a stable microsystems texture analyser (TA.XT plus, stable microsystems, Godalming, Surrey, UK) with a load cell capacity of 50 Kg and data processed and recorded by Exponent® system software (TA.XT plus, stable microsystems, Godalming, Surrey, UK).

The test was conducted at a crosshead speed of 5 mm/sec using a rectangular warner bratzler probe. Samples were deformed to 50% of their original thickness in two successive bites with no rest time between the bites. Each sample was tested three times by changing the deformation points in a way that the sample was divided into three equal parts, then their approximate centres marked and used as deformation points. Force deformation curves were generated by the Exponent® software (Texture, 2014) that yielded information on the product hardness, gumminess, cohesiveness, resilience, chewiness and springiness. Figure 3.7 presents a typical TPA force-time curve from which these parameters are calculated.

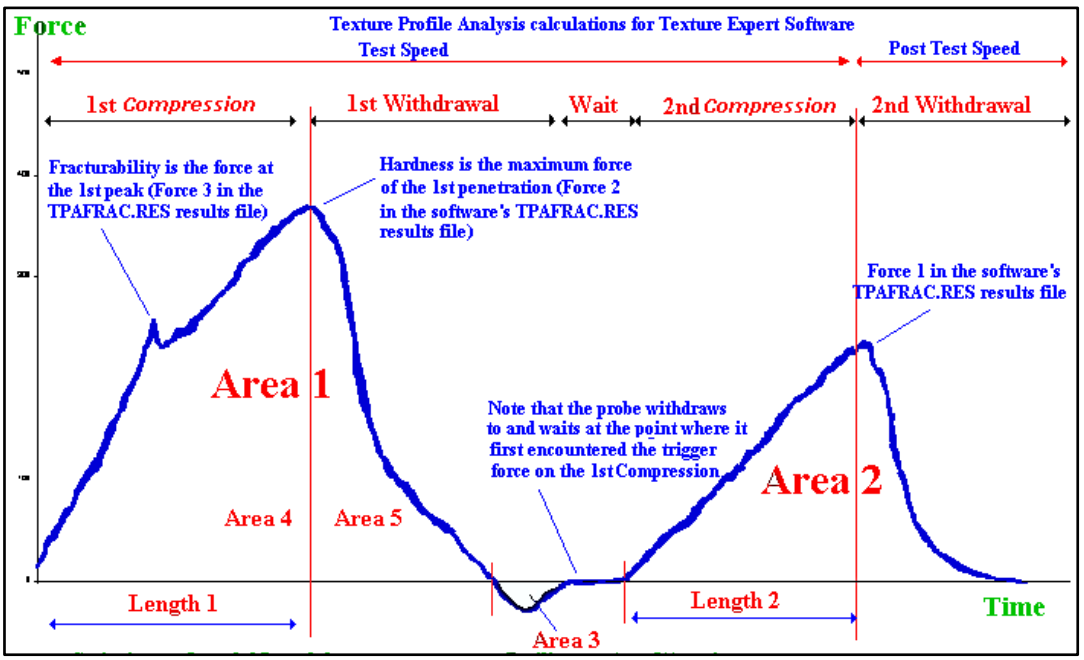


Figure 3.7A typical texture profile curve of biltong products (Texture Technologies, 2014)

Hardness is defined as the maximum force required to compress a sample, cohesiveness is the magnitude to which a food sample can be deformed before rapture, springiness is the ability of a food sample to regain its size after the deforming force is removed, gumminess is the force needed to break up a semi-solid sample to a condition that can be swallowed steadily and the chewiness is the work required to chew up a solid sample to a state that can be swallowed steadily (Martinez *et al.*, 2004). These parameters are calculated using equation 3.1 to 3.5 (Thiagarajan *et al.*, 2006; Thiagarajan, 2008).

$$\text{Cohesiveness} \quad \frac{\text{Area}}{\text{Area 2}} \tag{3.1}$$

$$\text{Gumminess} \quad \frac{\text{Area 2}}{\text{Area}} \quad \text{a rdness} \tag{ .2}$$

$$\text{Resilience} \quad \text{Gumminess} \quad \frac{\text{Length 2}}{\text{Length}} \tag{ . }$$

$$\text{Chewiness} \quad \frac{\text{Area 5}}{\text{Area}} \tag{ . }$$

$$\text{Springiness} \quad \frac{\text{Length 2}}{\text{Length}} \tag{ .5}$$

### 3.4.3 Rehydration

Rehydration measures the ability of processed food products to regain their original structural and raw material properties when they come into contact with water. This parameter is important in evaluating the extent of tissue damage after drying.

Rehydration of dried ready-to-eat (RTE) meat products is not commonly measured. From literature, only one article by Nathakaranakule *et al.* (2007) that measured the rehydration of dried meat was found. The rehydration behaviour of a dried RTE meat product is associated to its palatability. Rehydration tests were carried out according to the method used by Nathakaranakule *et al.* (2007), where a 10-15 g sample was put in hot water initially at 90$^{o}$C and rehydrated for 10 minutes. Its mass was measured in one-minute intervals by quickly removing it from the water, blotting excess water from the surface, weighing it and putting it back into the water. The process was repeated for each sample using three replicates; with a replicate constituting an unused sample that underwent the same pre-treatment and drying conditions. The percentage rehydration was calculated for each replicate using equation 2.24.

The rehydration rates of a sample were then computed by averaging the percentage rehydration of its replicates.

### 3.4.4 Shrinkage

For the evaluation of shrinkage, the sample slice of marinated biltong was measured for volume before and after drying. In this case, a marinated beef slice at the end of the marinating process was removed from the marinade and excess water removed from its surface using a blotting paper. The sample was then immersed in 100 $cm^3$ of distilled water in a 200 $cm^3$ graduated measuring cylinder. The volume of water displaced by the marinated sample was noted and the sample quickly removed from the measuring cylinder. Excess water was again removed from the sample's surface then labelled with a unique code to identify it from other samples in the same batch.

After drying, the volume of the dry biltong sample was again measured using the same procedure but with the aid of a sinker. Volume measurements were carried out in three replications, with a replicate constituting an unused sample that has undergone the same pre-treatment and drying condition. The shrinkage coefficient of each replicate was calculated using equation 3.6 (Maskan, 2001a; Thiagarajan, 2008), and the sample shrinkage coefficient was calculated by averaging the shrinkage coefficients of its three replicates.

$$\text{Shrinkage coefficient} \quad \left(1 - \left[\frac{V_f}{V_i}\right]\right) \quad 00 \qquad (\ .\ )$$

Where $V_f$ is the final volume of the samples and $V_i$ is the initial volume of the samples.

### 3.4.5 Microbial load (TVC)

**Coliform enumeration**

The total viable bacterial cells (TVC) were enumerated using the most probable number (MPN) method (Canadian Food Inspection Agency, 2002). A 10 g representative of dry samples from each dryer was obtained at random by cutting it off from one piece of biltong from its respective batch. Its mass was measured using an electric balance (CQ 200, Adam Core, UK) by putting it in a tarred autoclaved (at 121$^oC$) volumetric flask. Sterile saline peptone water (see Appendix J for full description) was then added to the 10 g biltong sample in the volumetric flask to give a mixture with a total mass of 100 g. This mixture was then homogenised in a sterilized food processor (FP120, Kenwood, UK) for 2 minutes at 2500 RPM. This undiluted homogenate, was designated the $10^{-0}$ dilution and was used to prepare

decimal dilutions using sterile saline peptone water and a pipette with sterile tips to the$10^{-5}$ dilution as demonstrated in Figure 3.8.

1 $cm^3$ of each serial dilution was inoculated in 5 ml, sterile standard 1 medium (see Appendix J for a full description) broth tubes, with 5 broth tubes being used per dilution.

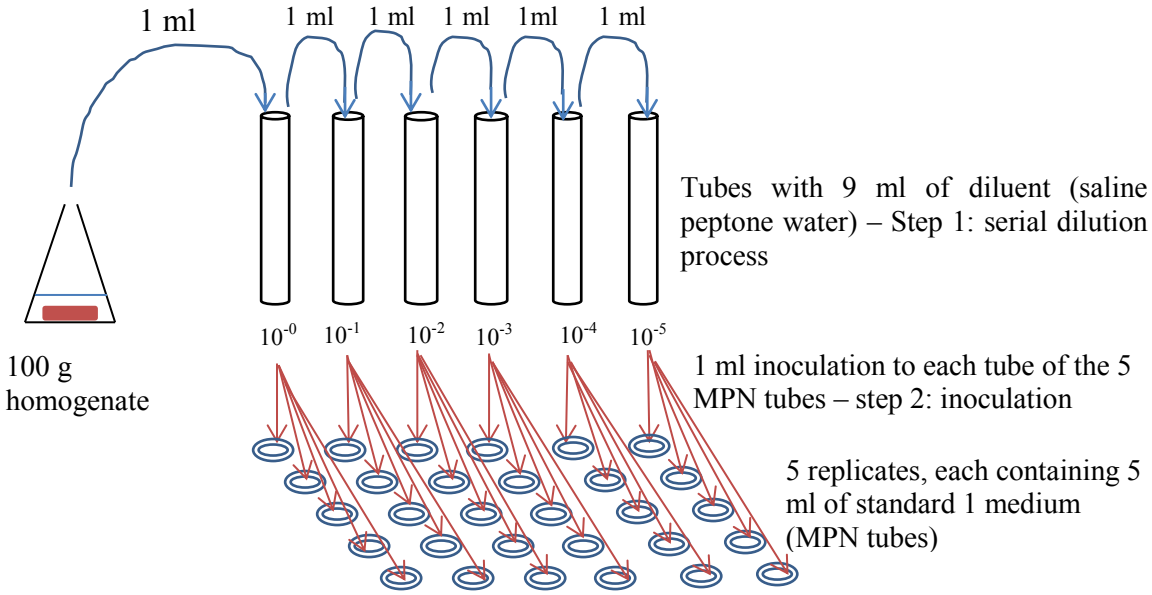


Figure 3.8 An Illustration of MPN procedure outlining the serial dilution process and the inoculation of decimal dilutions into the MPN tubes

The MPN tubes were incubated in a microbial incubator (Heraeus BB 6220, Thermo scientific Pty., South Africa) at a temperature of 35$^{o}$C for 24 hours. Gas-positive tubes indicated by a cloudy appearance (due to the microbial fermentation, hence the production of lactic acid) were counted and the value recorded after the first 24 hours. All the MPN tubes were incubated for a further 24 hours and the confirmation of gas-positive tubes was done again after this additional incubation time elapsed. This procedure was also applied to the freshly sliced beef samples. A 5 tube MPN statistical table (Man, 1983) was used to evaluate the MPN/g of viable bacterial cells in freshly sliced beef samples and dry samples dried under each of the drying systems assayed.

**Confirmation and identification of *E. Coli***

Each of the gas-positive broth tubes was shaken and a streaked loopful of the culture inoculated in eosin methylene blue (EMB) agar plates (Thermo scientific Pty., South Africa). The EMB plates were incubated for 24 hours at a temperature of 35$^{o}$C±2$^{o}$C (Heraeus BB

6220, Thermo scientific Pty., South Africa). They were, thereafter, visually inspected for the presence of nucleated, dark colonies with a green metallic sheen that is indicative of the presence of *E. coli* in the food sample.

## 3.5 Evaluation of Products' Drying Characteristics

### 3.5.1 Drying curves

Drying curves were prepared from the moisture loss data where each samples' mean moisture content at different times was calculated and plotted against drying time. In addition, from the moisture loss data, the moisture ratio values of the samples were calculated using equation 2.5. Subsequently, the drying rate was obtained using equation 2.6.

Matlab Version R2010a (MathWorks, USA) was used to differentiate the moisture content verses time curves to yield drying rate curves. In this case, the program's curve fitting toolbox was used. This tool was used as recommended by Kemp et al. (2001).

### 3.5.2 Drying models

Five commonly-used drying models were fitted to the experimental data using Matlab's curve fitting toolbox. These models were selected based on their excellent performance in predicting drying of food products on the basis of results in 52 published journal articles (see Appendix A) evaluated and similar work that had been carried out on beef Jerky and Kaddid for comparison (Thiagarajan, 2008; Chabbouh *et al.*, 2013). A summary of these models is presented in Table 3.1.

Table 3.1 A summary of five drying models used to model the drying kinetics of convective air and infrared drying of biltong

| Number | Model name | Equation | Reference |
|---|---|---|---|
| 1 | Page Model | $MR = \exp(-kt^n)$ | (Hii *et al.*, 2008) |
| 2 | Approximation of diffusion Model (ADM) | $MR = a\exp(-kt)+(1-a)\exp(-kbt)$ | (Botelho *et al.*, 2011) |
| 3 | Logarithmic Model | $MR = a\exp(-kt) + c$ | (Wang *et al.*, 2007) |
| 4 | Simplified Fick's Diffusion Model (SFD) | $MR = a\exp(-k(t/L^2))$ | (Mahdhaoui *et al.*, 2013) |
| 5 | Midilli Model | $MR = a\exp(-k(t^n))+b*t$ | (Midilli *et al.*, 2002) |

Where MR is dimensionless moisture ratio, L is sample thickness in meters, k is the drying constant in $hr^{-1}$ and t the drying time in hours. n, a, b and c are model coefficients.

### 3.5.3 Specific energy consumption (SEC)

The measured, energy consumption in kWh for each drying run was converted to MJ and the mass of water removed per drying run in kg, calculated from the moisture loss data. These were used in equation 3.7 to calculate the SEC of each infrared heater for each drying run.

$$\text{SEC} \quad \frac{\text{Energy consumed (MJ)}}{\text{ater removed (kg)}} \qquad (\ .7)$$

## 3.6 Data Analysis

Three factor ANOVA was carried out to evaluate the effects of the main factors on the drying characteristics and the product quality, as well as interacting factors with $\alpha \quad 0.05$. Separation of means was carried out using Fisher's least significant difference (LSD) test. All statistical analyses were carried out using IBM SPSS statistics version 21 (IBM corporation, USA). Before the ANOVA tests, it was first ensured that the data met normality and homogeneity of variances test, these being the prerequisites that statistical data should meet for ANOVA results to be valid.

Paired 2-tailed sample t-tests, were also used to evaluate the effect of different pre-treatment and drying systems on the product drying rates and the product core temperature of the infrared- dried samples.

# 4. RESULTS AND DISCUSSION

## 4.1 Initial Moisture Content

Figure 4.1 presents the changes in moisture content with marinating time for different biltong products. The initial moisture content of the beef slices of different thicknesses before marination, as can be seen in Figure 4.1, ranged between 75.33±0.43% wb for the 5 mm thick slices to 75.73±0.47% wb for 15 mm thick slices. Although it would appear that there is an increase in the moisture content with thickness, these differences are not statistically significant ($p \geq 0.05$) and the minor differences might have been caused by water losses during sample preparation. Although there appears to be a pronounced drop in the moisture content of the marinated samples of all thicknesses in the first 6 hours of marination, this reduction is not statistically significant ($p \geq 0.05$).

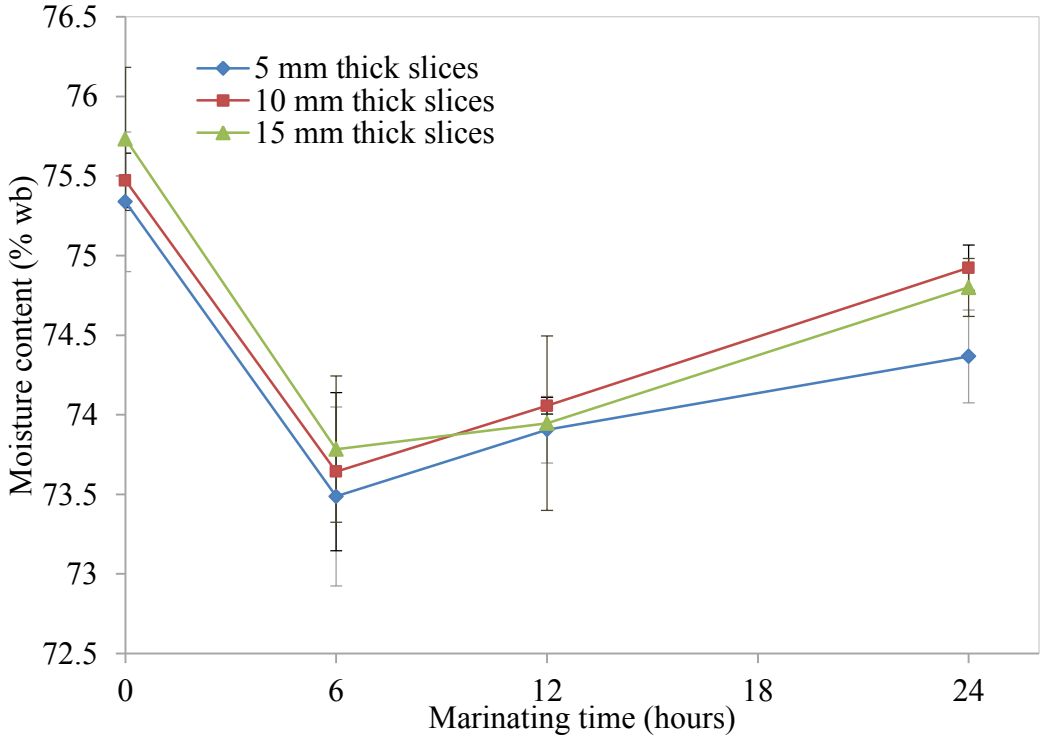


Figure 4.1 Effect of marinating duration on the moisture content of various samples.

The moisture content of the samples increased with increasing marinating duration between the 6 and 12 hour duration as can be observed in figure 4.1. At the 12-hour marinating duration, the 10 mm thick slices had higher moisture content than both the 5 and 10 mm thick slices. The differences in moisture content of the samples of different thicknesses at this point (12-hour marination), is not statistically significant ($p \geq 0.05$). When the marinating duration

was increased from 12 hours to 24 hours, there is a further increase in the moisture content of the samples, regardless of their respective thicknesses. The differences in moisture content between samples of different thicknesses at this point (24 hour marinating time), is also not statistically significant ($p \geq 0.05$).

Limited studies have been carried out on the diffusion dynamics of water into the hydration sites of marinated meats as a function of geometrical configurations of the marinated products (Yusop *et al.*, 2010). Generally, still marination is a process that is driven primarily by the prevailing process osmotic gradients (Sams, 2000). A drop in the sample moisture content at the 0 to 6 hour marinating interval is expected due to the diffusion of water out of the muscle tissue and uptake of salt (biltong spice is made of 90% salt) into the meat slices to a point (in this case close to the 6 hour marinating duration) where the osmotic equilibrium shifts due to the increase in water-binding sites in the samples. The 15 mm thick samples are expected to record the highest moisture content due to a higher relative proportion of myofibrils that constitute the primary hydration sites in marinated meat products (Yusop *et al.*, 2010). Adhesion of marinade's solid particles on the products' surfaces may have had an effect on the 15 mm thick samples due to its higher surface area.

In general, the marinating duration and the product thickness did not have a significant ($p \geq 0.05$) effect on the moisture content of the marinated beef samples and therefore, the products were of relatively uniform moisture content before the drying process.

## 4.2 Drying Characteristics

### 4.2.1 Visual observations

All the dry samples shrank when compared to the freshly marinated samples, although those dried using the convective dryer appeared to have shrunk more compared to the samples dried using the two infrared heaters. The surface exposed directly to the infrared radiation appeared to have shrunk more compared to the other surfaces for all dried samples due to high thermal gradients at this surface hence increased strain due to rapid moisture loss. Drying also caused changes in colour of dried biltong. Samples dried under the convective dryer were darker than those dried under both the LWL and HWL infrared heaters. Similarly, samples dried under the infrared heaters appeared to be redder than those dried under the convective dryer.

During the drying process, samples that were dried under the infrared heaters sweated during the final half of the drying period. This phenomenon was particularly pronounced in LWL infrared dried samples. Luikov (1975) derived equations that explain the mechanisms for moisture migration during the drying process of food products. Internal limits and external limits exist that can limit the moisture removal rates from a food material. Sweating in this situation, can be explained by the external moisture migration limit, where infrared radiation rapidly penetrated the food matrix heating the food and rapidly causing moisture to migrate to the surface. However, natural convection caused the exchange and movement of moisture from the product's surface to the surrounding air to reach an external moisture transfer limit, resulting in the condensation of vapour over the product's surface.

### 4.2.2 Product temperature

The temperature of the samples varied with the product marinating time, its thickness and the drying systems used to dry the product. The temperatures of samples under the two infrared dyers were logged in at suitable intervals. The sample temperature in the convective air drying system was assumed to be at about the equipment set-point temperature and is therefore, not discussed in this section.

**High wavelength (HWL) Infrared heater**

Figure 4.2 presents variations in product temperature with drying time for the 5 mm thick biltong slices previously marinated for 6, 12 and 24 hours. It can be seen from Figure 4.2 that the initial temperature of the samples was 26.78±1.92$^{o}$C. The temperature increased rapidly in the first 0.5 hours as seen in Figure 4.2. The temperature of 5 mm thick, 6-hour marinated samples rose to about 59.71$^{o}$C in 7 hours, while that of the 12-hour marination rose to 59.74$^{o}$C after 8 hours. The 24-hour marinated samples rose to 59.94$^{o}$C after 17.5 hours and its temperature appears to have stabilized at 61.09$^{o}$C after 19 hours. Clearly, the temperature rise is related to the degree of marination.

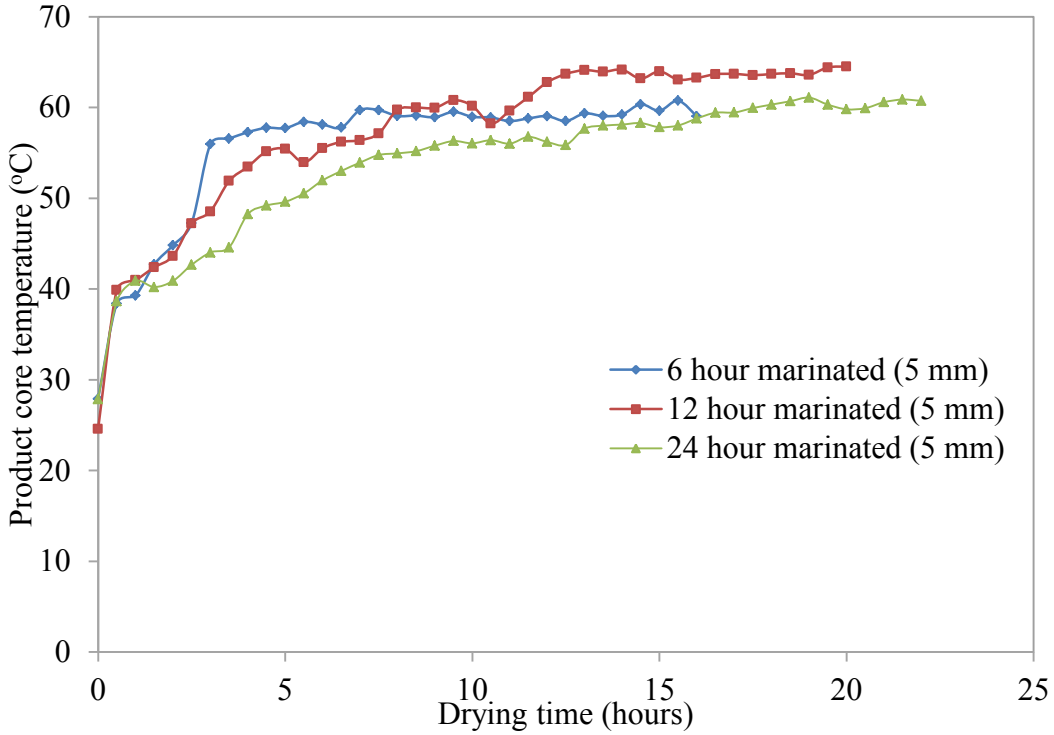


Figure 4.2 Changes in Product temperature with drying time, when the marinating duration was varied for samples that were dried under a high wavelength (HWL) infrared heater

The temperature of the 6-hour marinated samples was not significantly ($p \geq 0.05$) different from that of the 12-hour marinated samples. However, the temperature of the 6-hour marinated samples was significantly ($p \leq 0.05$) different from the 24-hour marinated samples and that of the 12-hour marinated samples was also significantly ($p \leq 0.05$) different from the temperature of 24-hour marinated samples.

It can be seen in Figure 4.2 that the increase in product temperature occurs within the first 5 hours. The product temperatures were generally lower with increasing marinating time, although the 12-hour marinated samples stabilized at higher temperatures compared to both the 6 and 24-hour marinated samples. Samples of other thicknesses (10 and 15 mm) that were marinated for 6, 12 and 24 behaved in a similar way, although 10 mm thick samples that were marinated for 6, 12 and 24 hours had significant differences ($p \geq 0.05$) in all sample product temperatures. The temperatures of the 15 mm thick samples were also significantly different for all marinating durations ($p \leq 0.05$). Appendix B presents additional data for product temperature variations of samples of other thicknesses that were marinated for different durations then dried under the HWL infrared heater.

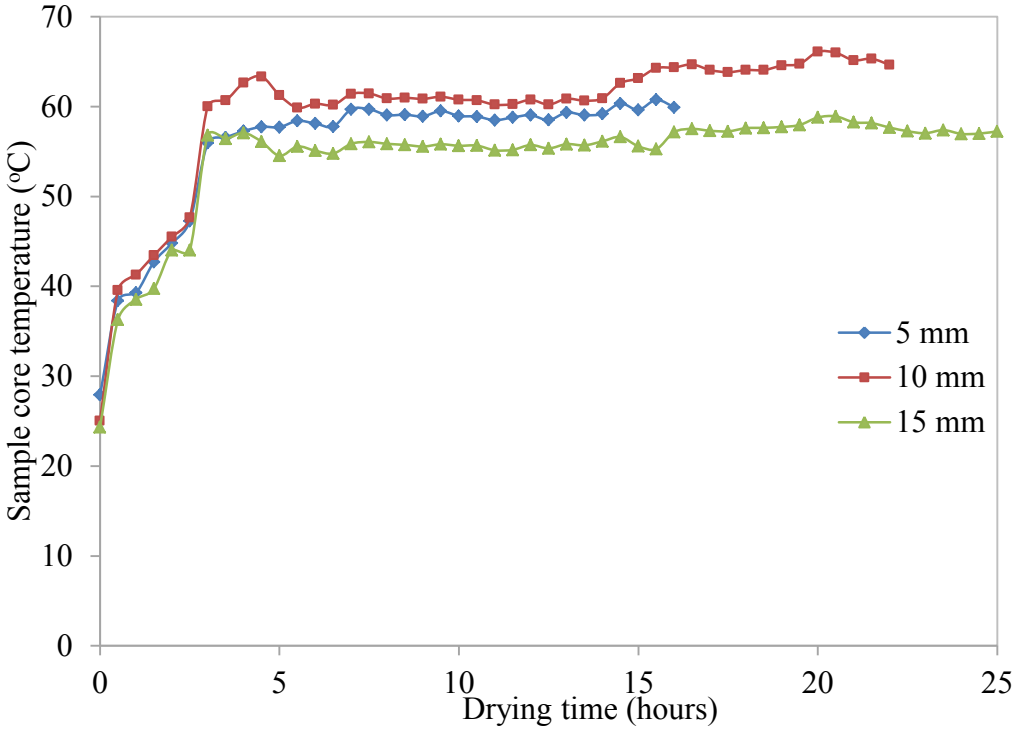


Figure 4.3 Changes in product temperature with drying time, with variations in sample thickness, for a fixed marinating time (6 hours) for samples the high wavelength (HWL) infrared dried samples

Figure 4.3 shows temperature variations with drying time for 6-hour marinated HWL infrared dried samples of various thicknesses and is representative of biltong samples that were marinated for 12 and 24 hours then dried under the same conditions (see Appendix B). The initial temperature of the samples was 25.76±1.89°C and it can be observed from Figure 4.3 that the temperatures of the samples of all thicknesses increased rapidly in the first 0.5 hours and appeared to have stabilized after 5 hours of drying. The stable temperature of the 5 mm thick samples was 59.71°C after 7 hours of drying, while the temperature of 10 mm thick biltong samples had risen to 63.75°C after 4.5 hours of drying. The temperature of 15 mm thick samples had risen to 58.79°C after 20 hours of drying.

The slice thicknesses clearly had an effect on the temperature of the product as can be seen in Figure 4.3. In this case, the temperature of samples of all thicknesses was significantly different ($p \leq 0.05$). The samples of other marinating durations (see Appendix B) that were dried under the same conditions behaved in a similar manner. However, the temperature difference between samples of 5 and 15 mm were not significant ($p \geq 0.05$). There was significant ($p \leq 0.05$) temperature differences between 5, 10 and 15 mm slices that were previously marinated for 24 hours. The 15 mm thick slices generally had the lowest product

temperatures of all the marinating durations. Samples that had thicknesses of 10 mm and had been marinated for 6 hours gave the maximum temperature of 66.09°C, for all samples dried under the HWL infrared heater indicating ideal infrared penetration at this thickness.

**Low wavelength (LWL) Infrared heater**

Figure 4.4 shows product temperature variations with drying time and marinating duration, for 10 mm thick, LWL infrared dried samples and is typical of samples other thicknesses previously marinated for different durations before drying under the same conditions (see Appendix B).

From Figure 4.4, it can be seen that the initial temperature of the samples was 29.13± 1.99°C. The temperature of the samples increased rapidly initially and appeared to have stabilized towards the end of the drying period.

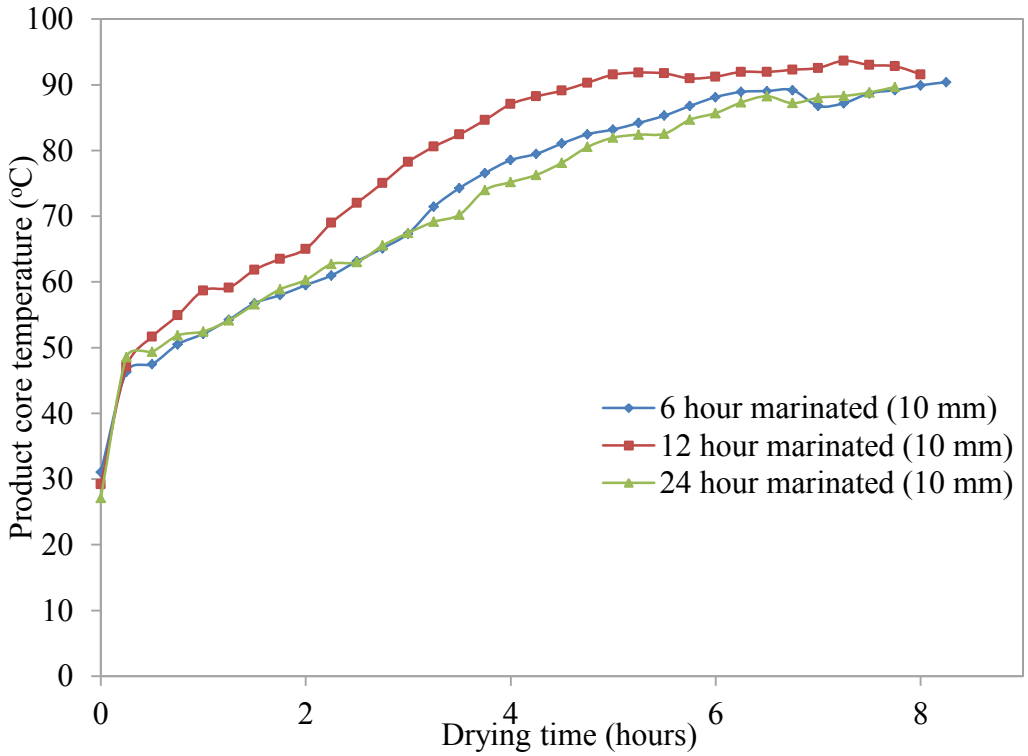


Figure 4.4 Changes in Product temperature with drying time, when the marinating duration was varied for samples that were dried under a low wavelength (LWL) infrared heater

It can also be seen that the temperature of the 6-hour marinated biltong slices rose to 88.12°C in 6 hours, while that of the 12-hour marinated biltong slices rose to 91.54°C after drying for 5 hours. The temperature of the 24-hour marinated biltong slices was about 88°C after 7 hours. The marinating duration had an effect on the product temperature with temperature of

samples of all marinating durations depicted in Figure 4.4 being significantly different ($p \leq 0.05$). Samples of other thicknesses that were dried under the same conditions exhibited similar behaviour, although the 5 mm thick, 6- and 24- hour marinated samples that were dried under the LWL infrared heater, had no significant difference ($p \geq 0.05$) in their product temperature. The difference in product temperature of the 6- and 24-hour marinated samples, as well as 12- and 24-hour marinated samples was significant ($p \leq 0.05$). In the case of 15 mm thick samples, differences in sample temperature for all marinating durations were significant ($p \leq 0.05$).

The product temperature of samples that were dried under the LWL infrared heater, generally increased with increasing marinating time. This trend applied to all product thicknesses, although samples that were marinated for 12 hours reached higher temperatures than those that were marinated for 6 hours and 24 hours (Figure 4.4). This trend was observed for products thicknesses of 5 and 15 mm (see Appendix B), although not for the entire drying period.

Figure 4.5 shows temperature variations with drying time for the 12-hour marinated, 5, 10, and 15 mm thick, HWL infrared dried samples and is typical for samples of other marinating durations that were dried under the same conditions. It can be seen in that the samples had an initial temperature of $29.63 \pm 0.68^{o}C$ and rose rapidly in the first four hours for all the samples, with the temperature of the 10 mm thick samples appearing to have stabilized at a temperature of about $91^{o}C$ towards the end of the drying period. The temperature of the 5 and 15 mm thick samples did not appear to completely stabilize during the entire drying duration, but the rate of increase in product temperature with time decreased with increasing drying time. The 5 mm thick slices recorded the highest maximum temperature of $103^{o}C$ for all thicknesses in this study, and were generally the highest temperature for all thicknesses, during the last half of the entire drying period. This was observed for samples of all marinating durations (Figure 4.5).

The temperature difference of samples of different product thicknesses was significant ($p \leq 0.05$) as can be deduced in Figure 4.5. Similarly, samples of 6 and 24 hour marinating durations (Appendix B) had significant differences in the product temperature between samples of all thickness. It can therefore be concluded that the slice thickness had a significant effect on the product temperature when dried under the LWL infrared heater.

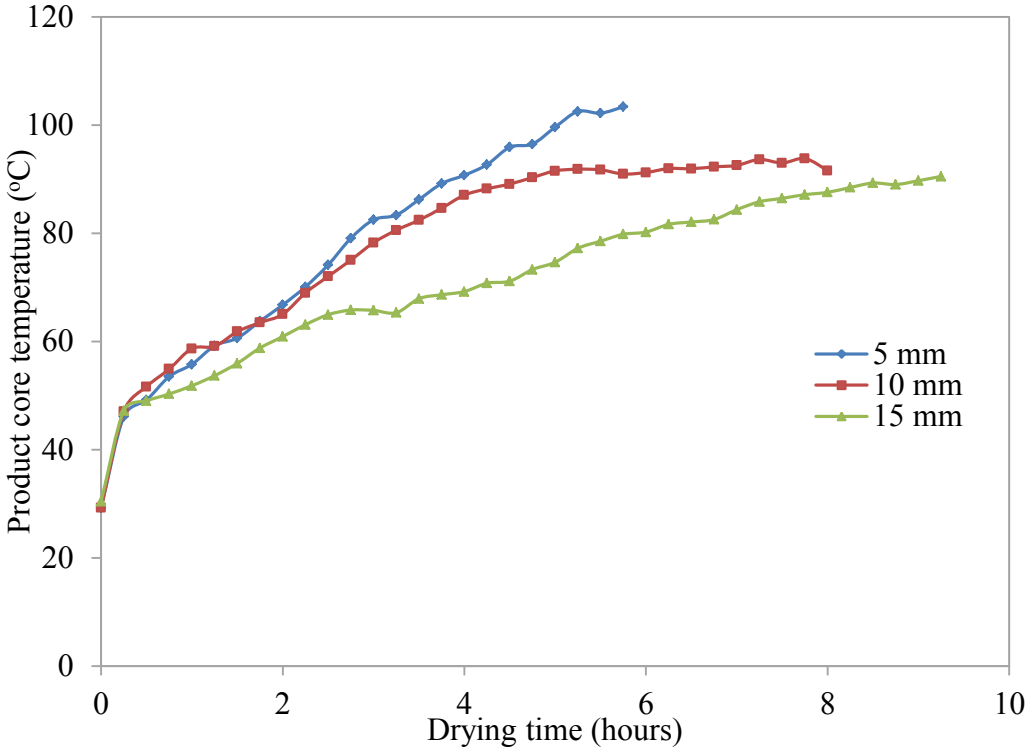


Figure 4.5 Changes in product temperature with drying time, with variations in sample thickness, for a fixed marinating time (12 hours) for samples the low wavelength (LWL) infrared dried samples

Generally, there was a rapid initial rise in product temperature for the products dried under both infrared systems. Initially, there was rapid heating of the water within the product as infrared radiation was intercepted. This resulted in the vapourization of water within the product followed by a cooling effect as the vapour moves out of the product. As more of the water in the product is removed, there is less and less infrared interception (since this is dependent on moisture content) and this slows down the rate of temperature rise towards the end of the drying process.

**Effects of different infrared heaters on the product temperature**

The temperature of samples dried under the LWL Infrared heater was significantly ($p \leq 0.05$) higher than those dried under the HWL Infrared heater for all product thicknesses and marinating times. The mean temperatures of samples dried under the two drying systems had the 12-hour marinated samples recording the highest temperatures for both the LWL and HWL infrared heaters. Samples dried under the HWL infrared heater had their average temperature increase for all thicknesses during the 6-12 hour-marinating interval, and reduced during the 12-24 hour-marinating interval but to a level lower than the 6-hour marinated samples. On the other hand, the average temperature of samples dried under the LWL

infrared heater increased during the 6-12 hour-marinating interval and reduced marginally in the 12-24 hour-marinating interval to a level higher than the 6 hour marinating duration. This was the case for samples of all thicknesses as depicted in Figure 4.6.

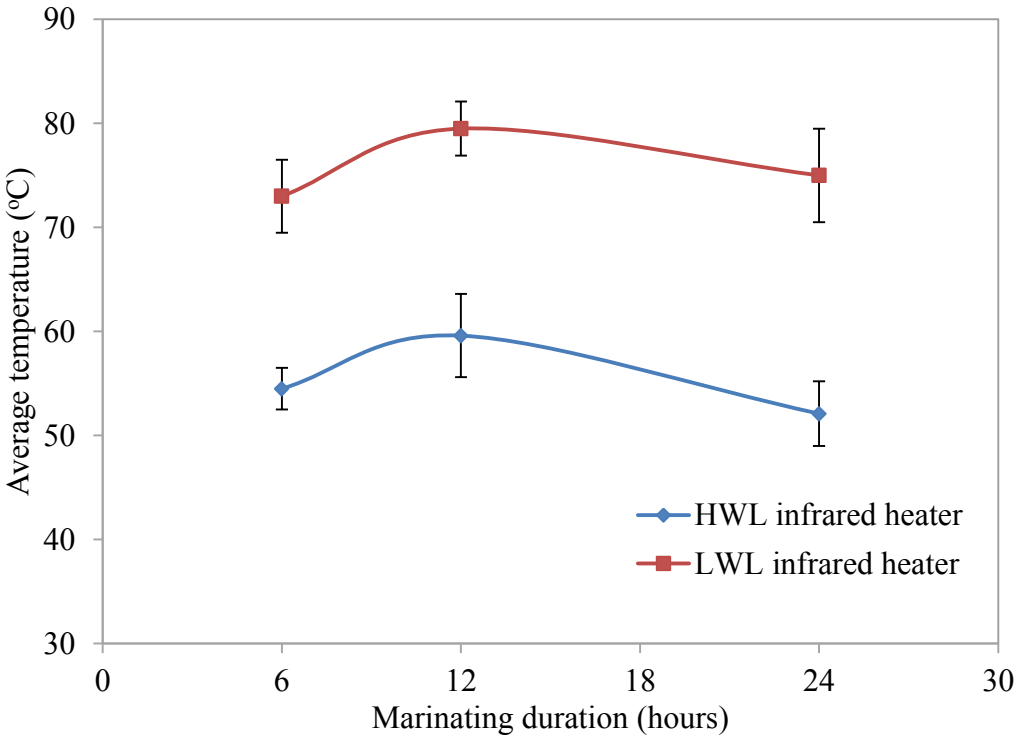


Figure 4.6 Comparison of the average product temperature for low wavelength (LWL) and high wavelength (HWL) infrared dried samples, relative to the marinating duration

The initial rate of increase in temperature of the samples was in the order, 6 hour marinating duration>12 hour marinating duration>24 hour marinating duration for the HWL and LWL infrared heaters in the initial drying period of 0-5 hours and 0-2 hours, respectively. Marinating meat chemically binds water within the meat muscle, in the tissue matrix (Smith and Acton, 2001). The change in the state of water in the product due to its interaction with different biochemical constituents in the meat may have made the meat products to absorb the radiation from the 2.5µm peak infrared heater more readily when the samples had been marinated for 12 hours. Similarly, the 3.5 µm peak infrared radiation from the HWL infrared heater may have been absorbed more readily at the point where the samples had been marinated for 12 hours, hence the occurrence of the maximum sample temperature at this marinating duration.

The penetrative power for the two infrared heaters based on the product temperatures suggests that the LWL infrared radiation penetrated the samples more than the HWL infrared radiation. In general, the LWL infrared radiation was more readily absorbed by the 5 mm samples causing their temperature to rise rapidly and to be higher than those of the 10 and 15 mm thick samples. Lin *et al.* (2009) dried apple slices of 5, 9 and 13 mm thickness, where the thinner samples heated up more rapidly than the thicker ones. They attributed the high product temperatures to high moisture content as it is assumed that far infrared radiation heats up products with high moisture content more rapidly than those with lower moisture content (Afzal *et al.*, 1999). This was true for HWL infrared dried 10 mm thick samples.

Generally, as indicated earlier, samples dried under the LWL infrared heater had higher average temperatures over the entire drying period, compared to those dried under the HWL infrared heater by 24.31$^{o}$C for the 5 mm thick slices, 18.21$^{o}$C for the 10 mm thick slices and 21.77$^{o}$C for the 15 mm thick slices. The temperature of samples of different marinating durations dried under the LWL infrared heater were higher than those dried under the HWL infrared heater by an average (over the entire drying period) of 22.77$^{o}$C for the 6- hour marinated samples, 19.91$^{o}$C for the 12-hour marinated samples and 19.55$^{o}$C for the 24- hour marinated samples. This accounts for the higher drying rates and shorter drying durations for the biltong products dried under the LWL infrared heater.

High moisture foods absorb infrared radiation more readily in the NIR region, with food such as potatoes, for example, having one of its peak absorption at 2.5 μm (Büning-Pfaue, 2003). Meat being one of the high moisture foods may have had infrared radiant heat from the 2.5 μm peak (LWL) infrared heater being absorbed more readily by the samples and thereby heating up faster than the 3.5 μm peak (HWL) infrared heater. The state of solutes (ions, organic monomers etc.) that water molecules bond with, affects the absorption bands of infrared radiation resulting in a shift of these absorption peaks toward higher or lower wavelengths depending on the hydration potential of the food and the solutes present (Büning-Pfaue, 2003).

The drying temperatures discussed above are likely to influence the drying times and drying rates of the samples that are discussed in the next sections.

### 4.2.3 Drying time

Drying time refers to the time taken for samples to reach the target moisture level of 20% ± 1% (wb). Drying time varied from 5.25 hours to 230 hours and depended on the product thickness, marinating duration or drying conditions. Generally, samples dried under the convective dryer had the longest drying time and those dried under the LWL infrared heater had the shortest drying time of all respective product thicknesses and marinating durations.

Figure 4.7 shows the drying curves of samples of 5, 10 and 15 mm thickness previously marinated for 6 hours then dried under the convective dryer conditions. These curves are typical curve shapes of 5, 10 and 15 mm thick, 12- and 24-hour marinated samples that were dried under the convective dryer (Appendix C). It is apparent that the moisture content decreased with increasing drying time (Figure 4.7) during the entire drying period. It can also be observed that the 5 mm thick slices had shorter drying times, compared to 10 and 15 mm thick slices. However, the difference in the drying time between 5 and 10 mm thick samples was only 5 hours while that between 10 and 15 mm thick samples was 40 hours. Generally, the drying time increased with an increase in slice thickness.

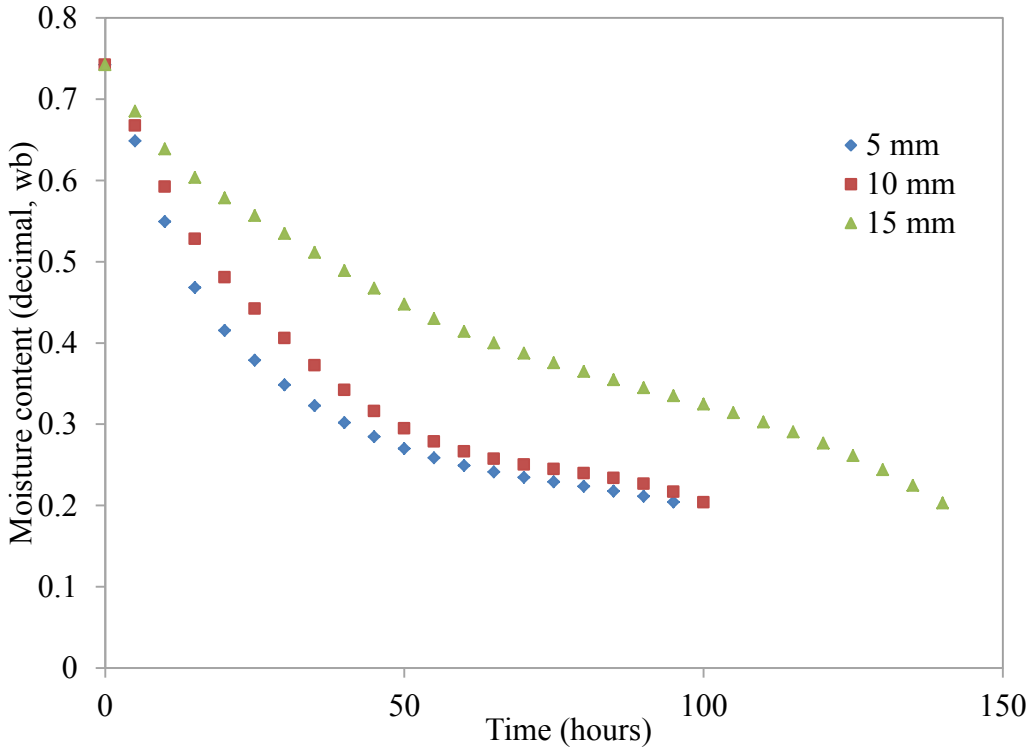


Figure 4.7 Changes in moisture content with drying time, when the slice thickness is varied for the convective air dried samples

Figure 4.8 shows the drying curves of 5 mm thick samples that were marinated for different durations before being dried under the convective air dryer. These curves are representative of the typical shape of the curves of biltong slices of other thicknesses that were marinated for different durations then dried using the convective dryer (see Appendix C). Clearly, it can be seen from Figure 4.8 that the 6-hour marinated samples dried faster (95 hours) than the 12-hour marinated samples (180 hours) and the 24-hour marinated samples (195 hours). Products of other thicknesses had their drying times increase with increasing marinating duration.

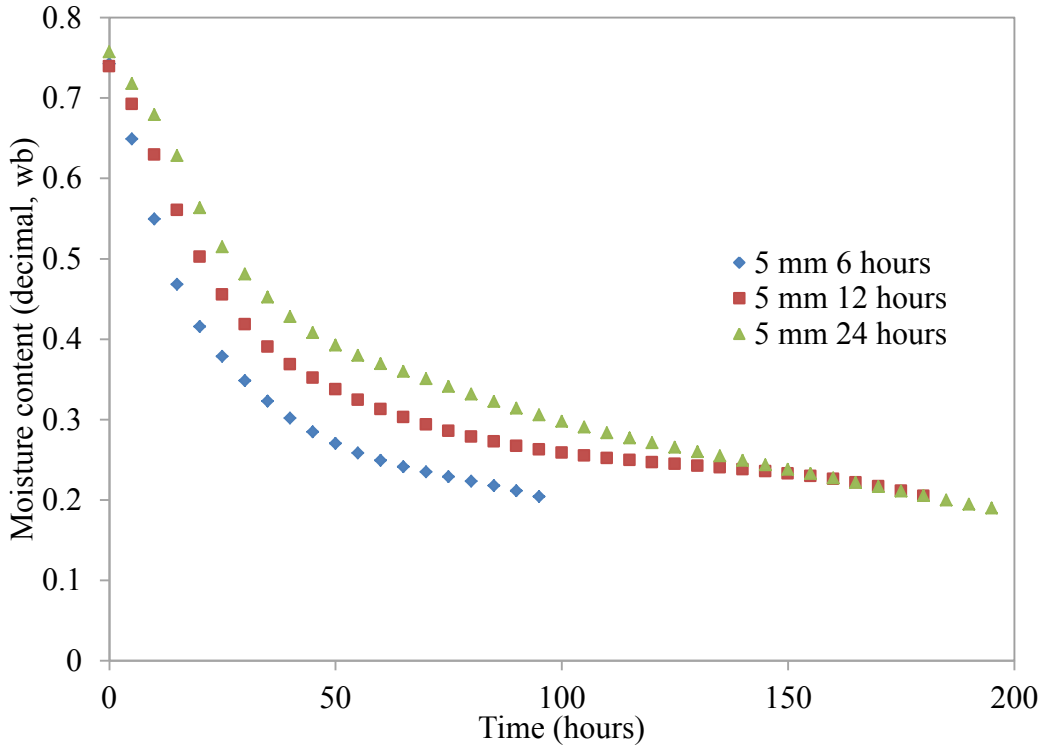


Figure 4.8 Changes in moisture content with drying time, when the marinating duration is varied for samples dried under the convective air dryer

From Figure 4.8, it can be seen that doubling the marinating time from 6 to 12 hours increases the drying time by 89%, while doubling it from 12 hours to 24 hours increases it only by 8%.

It can therefore, be concluded that under the given experimental conditions, an increase in the product thickness (Figure 4.7) as well as the marinating (Figure 4.8) duration results in an increase in the drying time for biltong products.

Figure 4.9 presents the drying curves of 5, 10 and 15 mm thick samples, previously marinated for 6 hours then dried under the LWL infrared heater. These curves represent the typical

shape of the curves of samples that were marinated for 12, and 24 hours then dried under the same conditions using the LWL infrared heater.

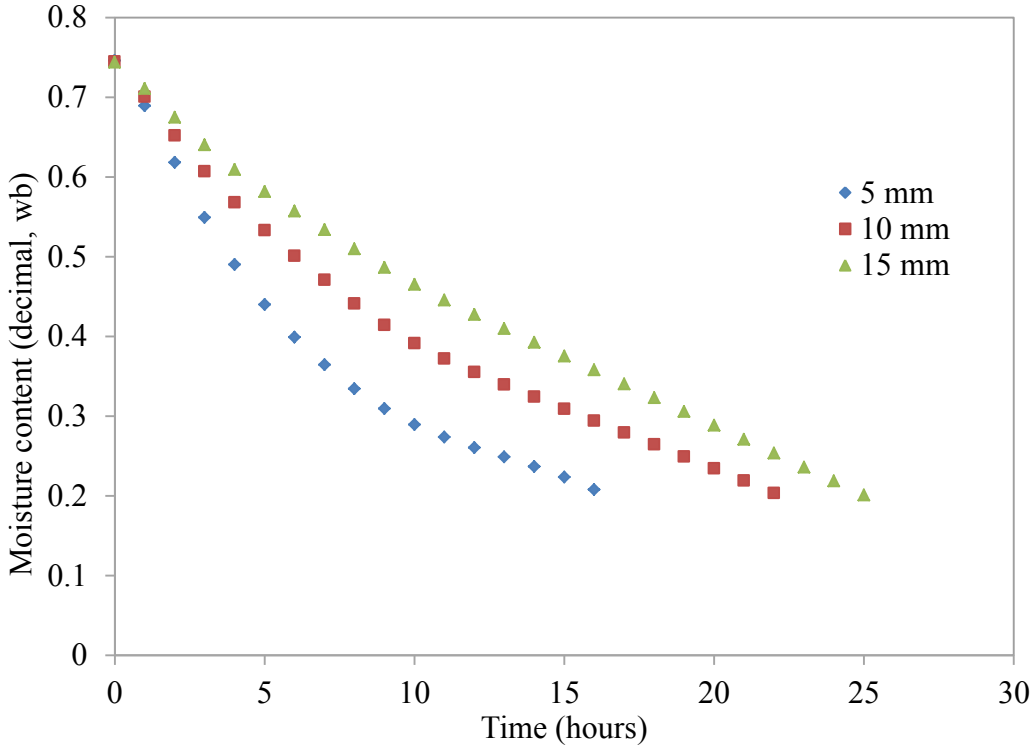


Figure 4.9 Changes in moisture content with drying time for the high wavelength (HWL) infrared drying of 6 hour marinated biltong slices.

The drying time for samples dried under the HWL infrared heater ranged from 16 hours to 36 hours. The drying time increased with increasing product thickness just like the case of products dried under the convective dryer, although the drying time was significantly ($p \leq 0.05$) shorter when compared to the drying time of the samples that were dried under the convective air dryer.

The 5 mm thick biltong slices (see Figure 4.9) had shorter drying times compared to the 10 and 15 mm thick biltong slices. The drying time increased by 37% when sample thickness was increased from 5 to 10 mm, while increasing by only 13% when the product thickness was increased from 10 to 15 mm.

Figure 4.10 depicts the drying curves of 5 mm thick samples previously marinated for 6, 12 and 24 hours then dried under the HWL infrared heater. Drying curves of 10 and 15 mm thick samples that were marinated for 6, 12 and 24 hours, then dried under the HWL infrared heater as shown in Appendix C). The drying times of the samples dried under the HWL infrared heater generally increased with increasing marinating times. Although Figure 4.10

represents only 5 mm thick slices, this trend was observed for all slice thicknesses dried under the HWL infrared heater. In addition, the difference in drying time due to marinating duration (Figure 4.10) is not as distinct as the difference due to product thickness (Figure 4.9). It can also be observed that the curves for the 24 hour and 12-hour marinated samples are close to each other.

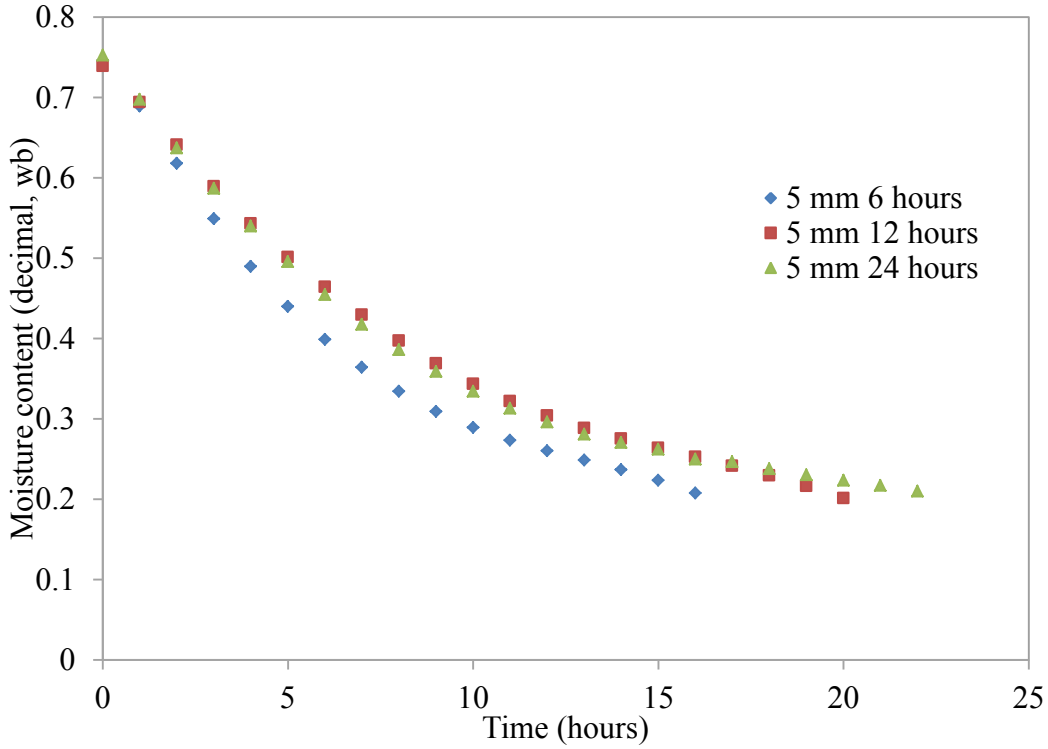


Figure 4.10 Changes in moisture content with drying time, when the marinating duration is varied for samples dried under the high wavelength (HWL) infrared heater

The samples that were dried under the LWL infrared heater had drying times ranging from 5.25 hours to 10.25 hours and was significantly ($p \leq 0.05$) shorter, when compared to those of the HWL infrared heater (16-36 hours) and those of the convective air dryer (95-230 hours).

Figure 4.11 shows the drying curves of biltong slices of different thicknesses previously marinated for 6 hours, then dried under the LWL infrared heater. These curves are typical shapes of the drying curves of samples of different thickness that were marinated for 12 and 24 hour durations then dried using the LWL infrared heater (see Appendix C).

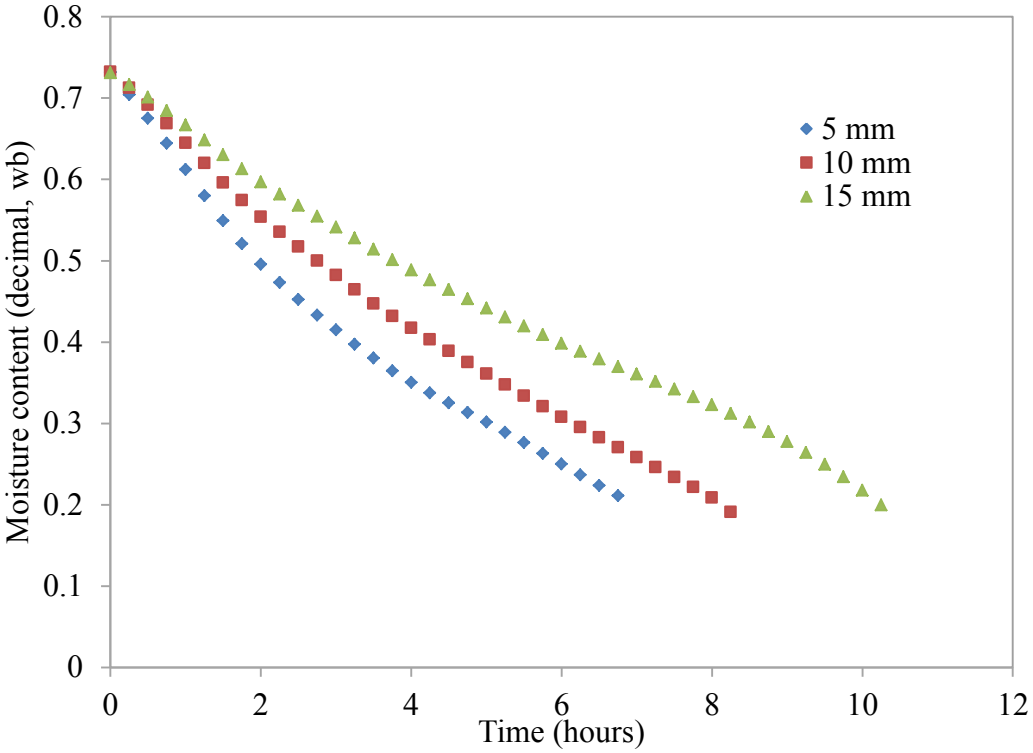


Figure 4.11 Changes in moisture content with drying time, when the slice thickness is varied for the low wavelength (LWL) infrared dried samples

It can be clearly seen that the 15 mm thick slices had drying durations that were longer compared to those of 10 and 5 mm thick slices. This trend was observed for all marinating times of samples dried under the LWL infrared heater (see Appendix C). It can be deduced (from Figure 4.11) that when the product thickness is increased from 5 to 10 mm, the drying time increased by 22% and when the thickness was further increased to 15 mm, the drying time increases by 24%.

Figure 4.12 shows the drying curves of the 6-hour marinated, 5 mm thick samples that were dried under the LWL infrared heater and is a typical representation of the general drying trends for samples dried under the LWL infrared heater. Increasing marinating durations for the 5 mm thick, LWL infrared dried samples, generally reduced the drying time. This trend was also true for samples of other thickness and marinating that were dried using the LWL infrared heater (Appendix C). It can also be deduced from Figure 4.12 that, as the marinating time is doubled from 6 to 12 hours, the drying time reduces by 2 hours while doubling it from 12 to 24 hours reduced the drying time by 0.5 hours.

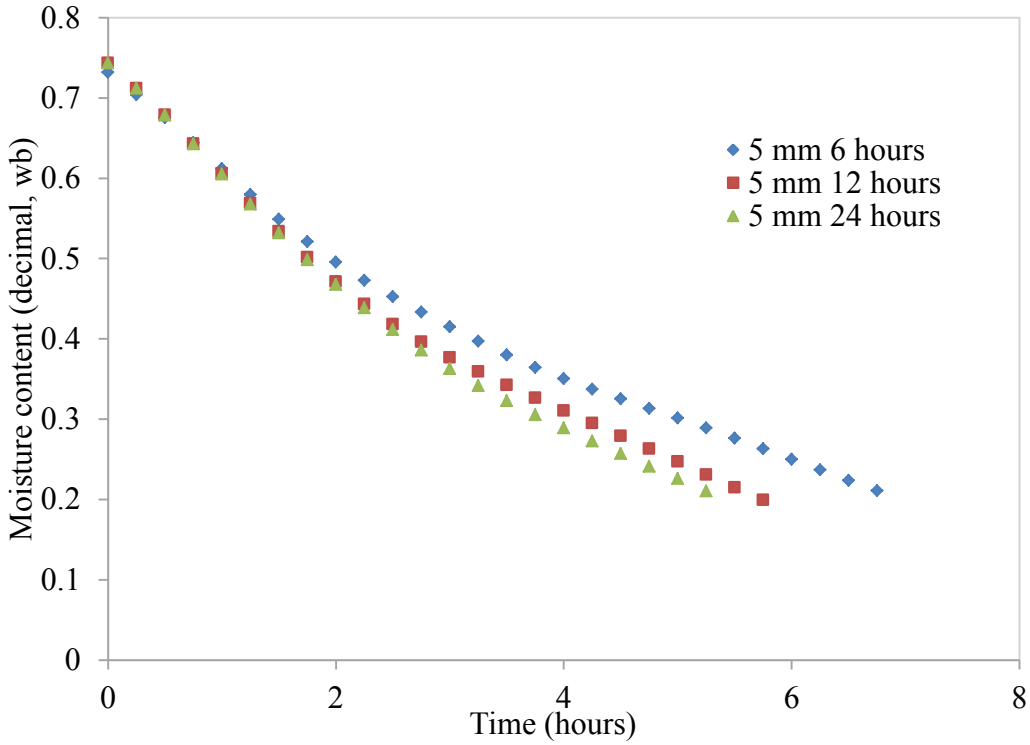


Figure 4.12 Changes in moisture content with drying time, when the marinating duration is varied for samples dried under the low wavelength (LWL) infrared heater

**Effects of the drying systems on product's drying time**

Comparison of the drying times of samples dried under different drying systems show that the LWL infrared heater was the fastest drying system. On the other hand, biltong slices dried under the convective air drying system had the longest drying times of all marinating conditions and product thicknesses, for the drying systems under this study.

The trend depicted by these results is corroborated by Wang and Shi (1999), where beef samples of different thicknesses influenced their drying time, with thinner samples giving shorter drying times due to their lower internal resistance to mass transfer and a higher internal heat generation rate. There is, however, a critical thickness size in their research where increasing thickness did not alter the drying times. This was not encountered in the present research probably due to differences in experimental conditions.

The drying times increased with increasing marinating time for samples that were dried under the convective air drying system and the HWL infrared heater while the converse was true for those dried under the LWL infrared heater. This phenomenon may be attributed to the differences in the peak wavelength of the energy from the HWL infrared heater when compared to the LWL infrared heater. Spicing is known to decrease the drying time of meat

products, while salting increases the drying time (Chabbouh *et al.*, 2013). However, with high drying temperatures, an increase in drying rate with increasing salting level is known to occur in salted food products, hence a decrease in the drying time (Lewicki, 2004).

A three-factor ANOVA was used to evaluate the effect of the different pre-treatment conditions and the drying systems on the drying time of biltong. It showed that there was a significant ($p \leq 0.05$) difference in drying time of different drying systems while minor differences were attributable to the product thickness and degree of marination.

The drying times for samples that were dried under the convective air drying system were 84.6% and 95.6% longer than the drying times for the samples that were dried under the HWL and LWL infrared heaters, respectively.

### 4.2.4 Drying rate

The drying rate of the samples varied according to the product thickness, marinating treatment or the drying system used to dry the product. The drying rate of 5, 10 and 15 mm thick samples as a function of moisture content, for the convective air dried, 6-hour marinated samples are shown in Figure 4.13.

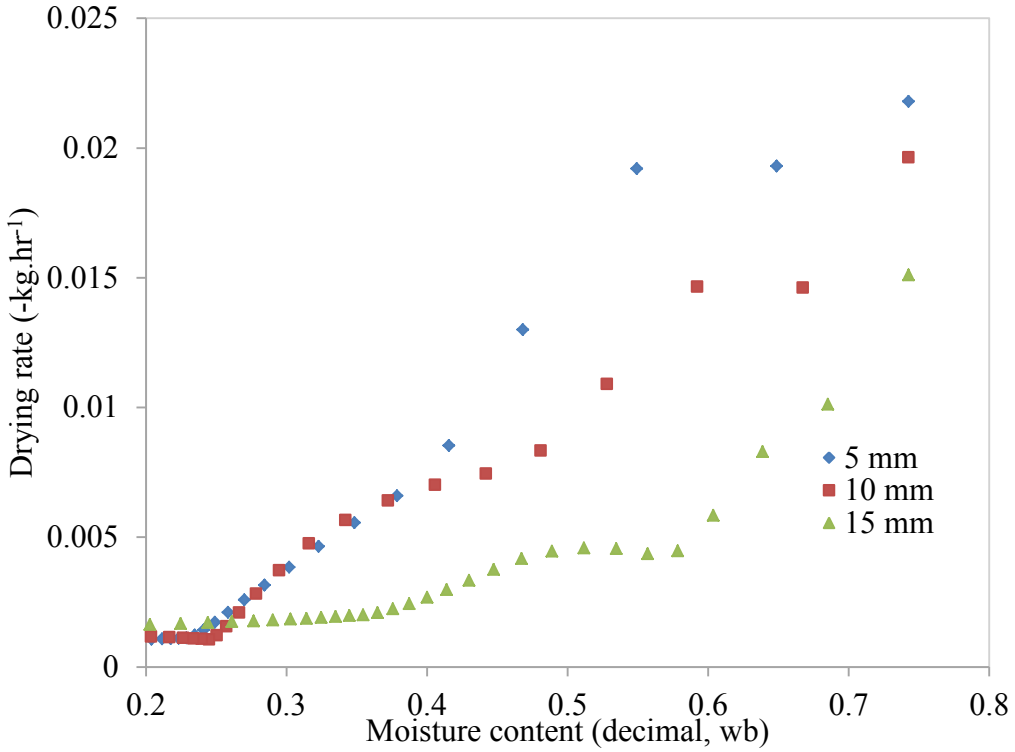


Figure 4.13 Changes in the drying rate as a function of moisture content, for the convective air dried samples, when the slice thickness is varied

It was noticed that samples had the highest drying rate soon after the beginning of the drying period. It initially decreased with decreasing moisture content and reached a constant rate, with a further decrease in moisture content. The drying rate decreased further, with decreasing moisture content up to the end of the drying period. The constant drying rate period was approximately 5 hours for 10 and 15 mm thick samples, and 25 hours for 15 mm thick samples (see appendix D). Samples of 5, 10 and 15 mm thickness, marinated for 12 and 24 hours (see appendix D) did not have a constant drying rate period.

Thin slices (5 mm) had the highest drying rates at the beginning of the drying period, but both the 10 mm and 5 mm thick samples appear to dry at almost the same drying rates towards the end of the drying period. There was significant ($p \leq 0.05$) difference in the drying rates between samples of different thicknesses that were marinated for 6 hours.

Figure 4.14 shows the drying rate curves of 5 mm thick samples that were marinated for different durations, and then dried under the convective air dryer. It was observed that the drying rates of the samples were highest close to the beginning of drying and that the 6-hour marinated samples had the highest drying rates for the entire drying period. A constant drying rate period was observed for the 6- and 24-hour marinated samples.

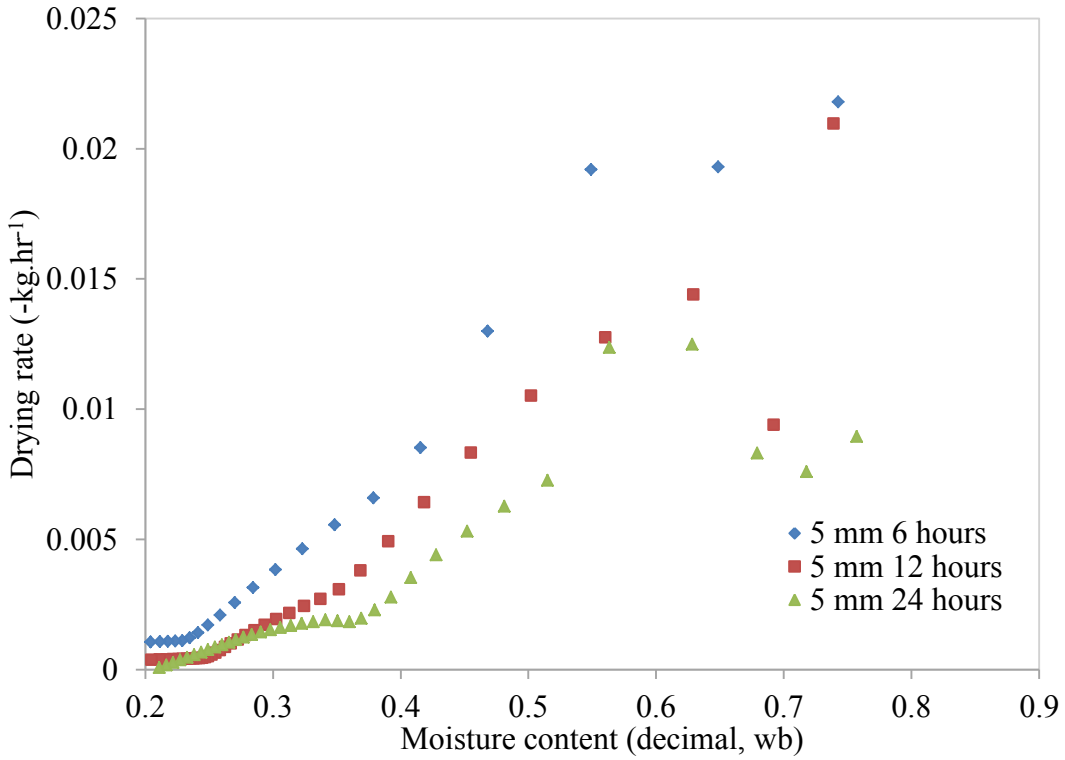


Figure 4.14 The drying rate as a function of moisture content during convective drying of biltong slices.

The 5 mm thick, 6-hour marinated samples had significantly ($p \leq 0.05$) higher drying rates compared to those of the 12 and 24 hour marinated samples of the same thickness. There was no significant ($p \geq 0.05$) difference in the drying rates of the 12 and 24 hour marinated slices (Figure 4.14). Clearly, the marinating duration had an effect on the drying rates of the samples, albeit not significant in all cases.

Figure 4.15 presents the drying rate curves of 12-hour marinated, LWL infrared dried samples of 5, 10 and 15 mm. The drying curves of samples marinated for 6 and 24 hours are presented Appendix D. It was observed that the drying rate of the samples was highest close to the beginning of drying, and that it initially increases at the beginning of drying, before falling with a further decrease in moisture content. Towards the end of the drying period, a constant rate was observed for 5 and 10 mm thick, 12-hour marinated samples that were dried under the HWL infrared heater (see appendix D). It can be further noted that the drying rate of the 5 mm thick samples was higher than that of 10 and 15 mm thick biltong slices for the entire drying period.

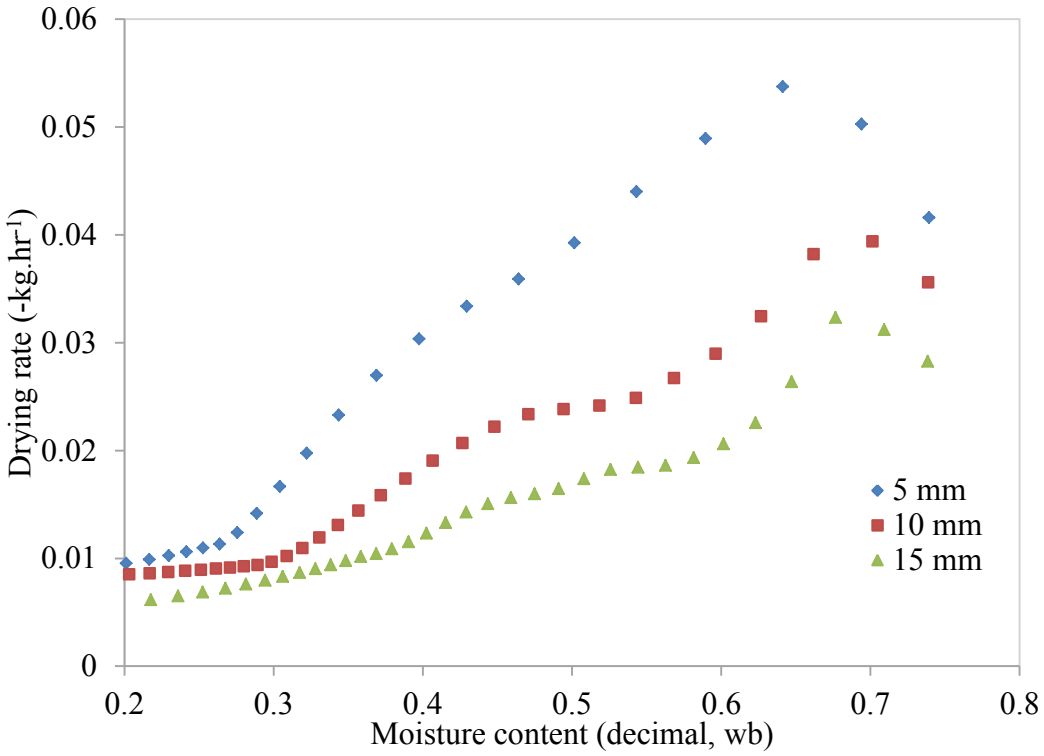


Figure 4.15 Changes in the drying rate as a function of moisture content, for the high wavelength (HWL) infrared dried samples, when the slice thickness is varied

The drying rate for the 12-hour marinated biltong slices was significantly different ($p \leq 0.05$) between samples of all thicknesses. The highest drying rates for the LWL infrared dried

samples of 5, 10 and 15 mm thickness samples was 0.073 kg.hr$^{-1}$, 0.048 kg.hr$^{-1}$ and 0.039 kg.hr$^{-1}$, respectively.

Figure 4.16 shows the drying rate curves of 5 mm thick, HWL infrared dried samples of 6-, 12- and 24-hour marinating durations. These curves are the typical (representative) shape of drying rate curves of samples any thickness or marinating duration of samples dried under HWL infrared heater. It is evident that the 5 mm thick, 6-hour marinated samples had a higher drying rate compared to the 5mm thick, 12 and 24-hour marinated samples. It can be further observed that the drying rate curves of 12- and 24-hour marinated samples are close.

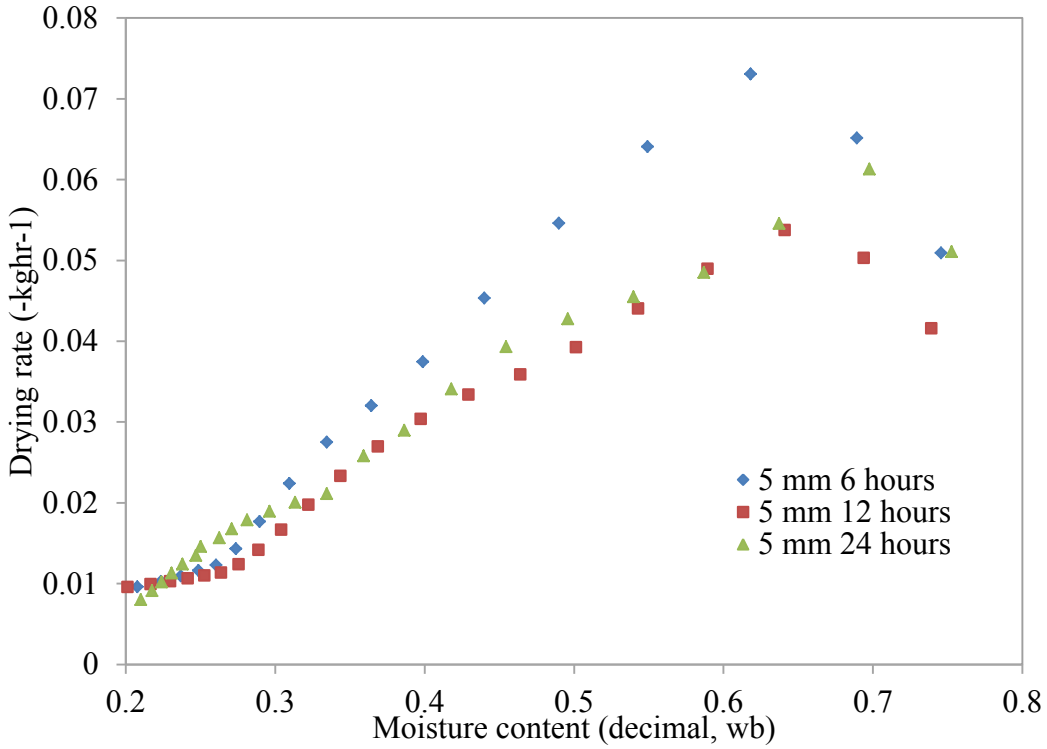


Figure 4.16 Changes in the drying rate as a function of moisture content, for the high wavelength (HWL) infrared dried samples, when the marinating duration is varied

There was a significant ($p \leq 0.05$) difference in the drying rate between 5 mm thick, 6- and 12-hour marinated samples, as well as between 6- and 24- hour marinating durations of the same thickness. There was, however, no significant ($p \geq 0.05$) difference in the drying rate of 5 mm thick samples that were marinated for 12 and 24 hours.

Figure 4.17 shows the drying rate curves of the 24-hour marinated, LWL infrared dried biltong products of various thicknesses. These curves are the typical (representative) shape of the drying rate curves of samples of different marinating durations and thicknesses dried

under the same conditions using the LWL infrared heater. It is evident that the drying rate initially increased with decreasing moisture content, reached a maximum and then fell with a further decrease in moisture content (Figure 4.17). It can also be observed that the drying rates increased with decreasing product thicknesses. A constant rate drying period was observed for the 5 mm thick samples at moisture contents below 28.89% (wb) and coinciding with a drying time of 4 to 5 hours (See appendix D).

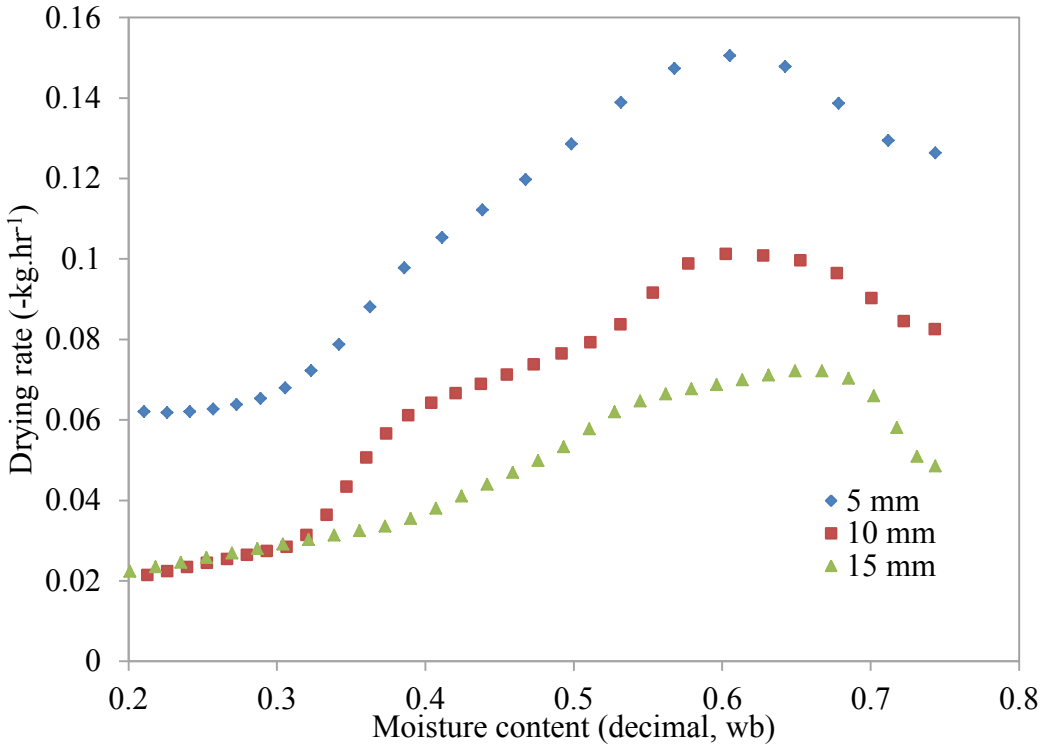


Figure 4.17 Changes in the drying rate as a function of moisture content, for the high wavelength (HWL) infrared dried samples, when the slice thickness is varied

The highest drying rates for the 5, 10 and 15 mm thick samples that were dried under the LWL infrared heater was 0.151 $kg.hr^{-1}$, 0.101 $kg.hr^{-1}$ and 0.074 $kg.hr^{-1}$, respectively. The drying rate for the 24-hour marinated, LWL infrared dried samples, of all thicknesses (5, 10 and 15 mm), was significantly ($p \leq 0.05$) different (Figure 4.17).

Figure 4.18 shows the drying rate curves of 5 mm thick samples, of various marinating durations that were under the LWL infrared heater. These curves are the typical (representative) shape of the drying rate curves of biltong products of other thicknesses (10 and 5 mm thick samples) that were dried under the same conditions using the LWL infrared heater. It was observed that the drying rates of the samples initially increased with decreasing moisture content, reached a maximum point and fell with further decrease in the product

moisture content (Figure 4.18). It can also be observed that the 12- and 24-hour marinated sample's drying rate curves appear to be close at the beginning of the drying period (between 74.37 to 53.19% wb moisture contents), and that the 24-hour marinated samples had the highest drying rate towards the end of the drying period (between moisture contents of 53.19 to 30.55% wb).

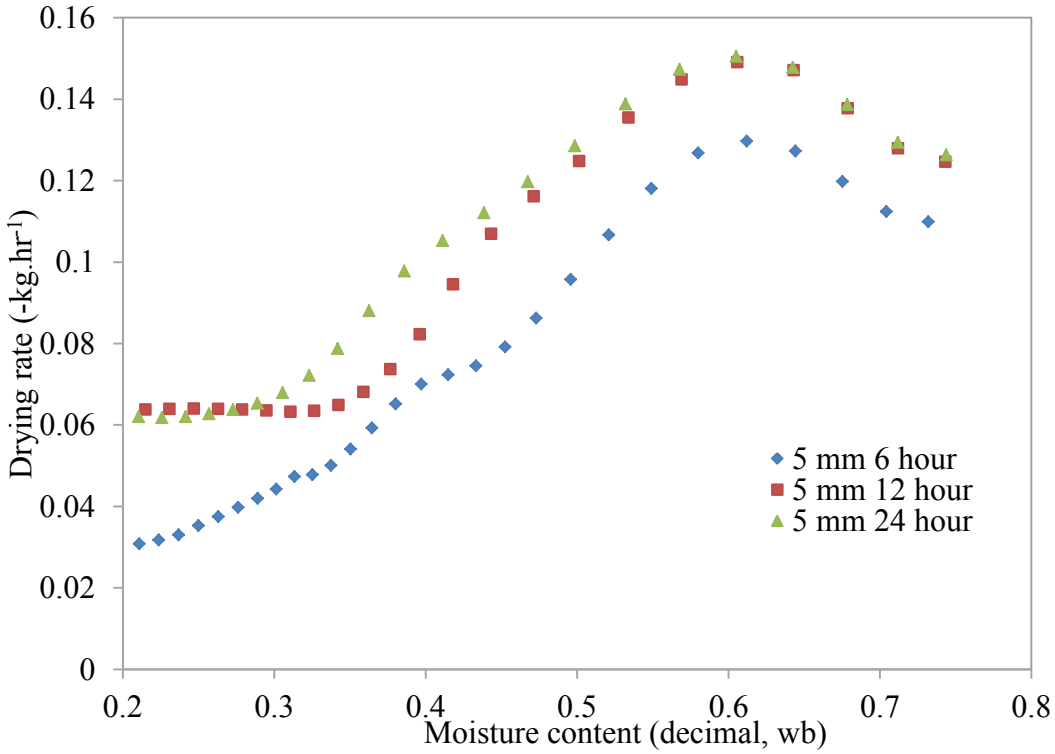


Figure 4.18 Changes in the drying rate as a function of moisture content, for the low wavelength (LWL) infrared dried samples, when the marinating duration is varied

The difference in drying rate between 5 mm thick, 6- and 12-hour marinated as well as between 6- and 24-hour marinated samples was significant ($p \leq 0.05$). However, there was no significant ($p \geq 0.05$) difference in the drying rate between 5 mm thick, 12- and 24-hour marinated samples that were dried under the LWL infrared heater.

Longer marinating times presume more salt and spice uptake by the samples (biltong spice is 90% salt). In addition, the solutes in the product mass influences the bonding conditions of the water present in the product. Chabbouh *et al.* (2013) showed that salting of beef prior to drying increases the drying time. Since biltong spice is 90% salt, their observations are therefore consistent with the results of the drying rate in the convective air dryer and the HWL infrared heater. The presence of spice and salt solutes in the beef matrix may have

changed the bonding conditions of the water present in the product by reducing the amounts of available and free water. With the supply of the same drying energy, the water in the samples marinated for a longer time had higher resistance to moisture removal than the samples marinated for shorter periods (Sabadini *et al.*, 1998). However, in cases where products dry at elevated temperatures (as was the case in the LWL infrared heater), high solute concentration causes rapid water loss (Sabadini *et al.*, 1998).

As expected, increase in product thickness increased the distance that moisture migrated through the product, and in turn, resulted in an increase in the degree of moisture resistance. The supply of more energy was therefore required to remove water from the products to the target moisture content. Heat energy also has better penetration and water removal capacity in thinner products than in thicker ones. Similar observations were reported by Adom *et al.* (1997) in their experiments where they dried okra in thicknesses of 5, 10 and 15 mm.

**Effects of the drying system on product's drying rate**

Comparison of drying rates of samples under different drying systems shows that the LWL infrared heater gave the highest drying rates for the three systems assayed regardless of the product thickness or marinating duration. The 5 mm thick, 24-hour marinated samples dried under the LWL infrared heater had the highest drying rates while the 15 mm, 24-hour marinated samples dried under the convective air drying system had the lowest drying rates. The infrared heaters also had higher drying rates compared to the convective drying system, consistent with some of the advantages of infrared drying cited in literature.

Infrared drying systems had comparable trends in product drying rate, with an initial rising period followed by a falling rate period. On the other hand, convective air systems had a falling drying rate period throughout. However, the 6-hour marinated convective air dried samples had a brief constant rate drying period. The drying rate curves for the infrared drying systems are similar to those reported by Kocabiyik and Tezer (2009). High temperature in the products dried using infrared systems removed free and loosely-bond water rapidly causing the drying rate to initially rise. As the free and loosely-bound water decreases, a greater proportion of the tightly-bound water is available for removal in the food matrix, hence a shift from an increasing rate of drying, to a falling phase to the end of the drying period. High drying temperatures have a higher potential for quick removal of free and loosely-bound water compared to lower drying temperatures, hence the general falling rate for the convective air dried samples.

Figure 4.19 shows a graphical comparison of the maximum drying rates of samples of different thicknesses as a function of the three drying systems tested. It can be deduced from this figure (Figure 4.19) that the maximum drying rate of samples dried under the LWL infrared heater was 51.2% and 85.6% higher than that of the HWL and convective air dryer respectively, for the 5 mm thick samples. The maximum drying rate of the LWL infrared dried samples was 52.2% and 80.6% higher than the drying rate of products dried under the HWL and convective dyer respectively (in the case of 10 mm samples), while the maximum drying rate of the LWL infrared dried samples was 47.2% and 79.6% higher than that of the HWL infrared heater and convective air dryer, respectively, for the 15 mm thick samples. Appendix L shows a graphical presentation of the variation of the maximum drying rate with marinating duration.

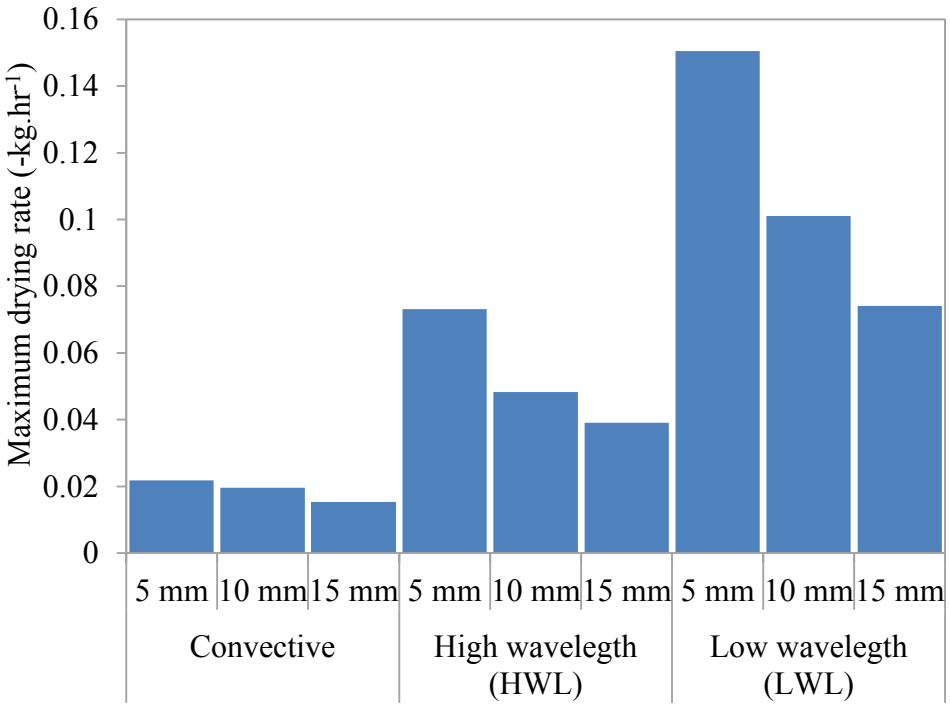


Figure 4.19 Comparison of the maximum drying rate as a function of the drying system used to dry samples of various thickness

### 4.2.5 Specific energy consumption (SEC)

The SEC of the HWL and LWL infrared heaters processing samples that were marinated for 6, 12 and 24 hours is shown in Figure 4.20. The SEC of samples dried under the HWL infrared heater increased by 24.5% when the marinating duration doubled from 6 to 12 hours, and increased by 8.5% when there was a further increase in the marinating duration from 12

to 24 hours. On the other hand, the SEC of samples that were dried under the LWL infrared dryer decreased by 13.2% when the marinating duration was doubled from 6 to 12 hours and further decreased by 18.7% when the marinating duration was again doubled from 12 to 24 hours.

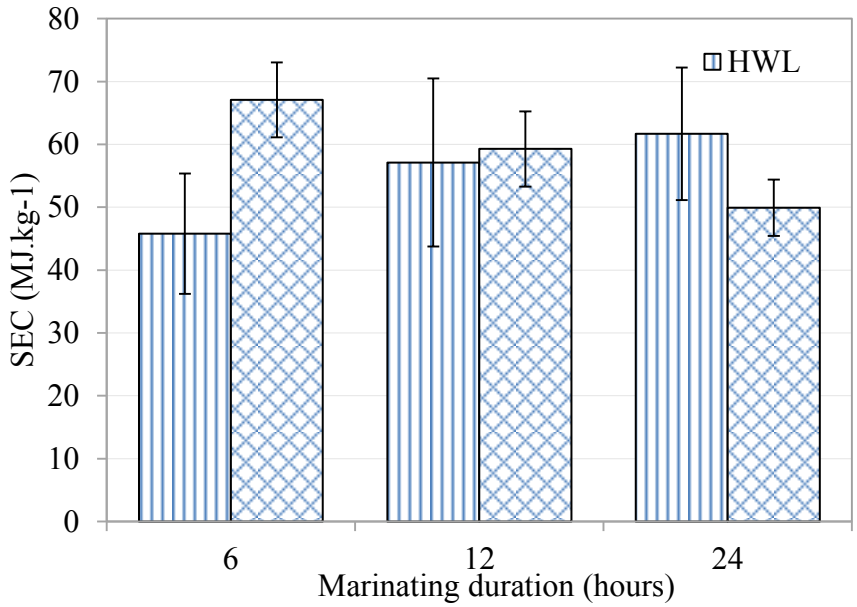


Figure 4.20 A side by side comparison of the specific energy consumption (SEC) as a function of the marinating duration, when biltong is dried under a high wavelength (HWL) or low wavelength (LWL) infrared heater

The infrared heating system used to dry the product as well as the marinating duration produced minor differences in the SEC consumption of the heaters. Although, the drying system (HWL or LWL) has a significant ($p \leq 0.05$) effect on the SEC of samples dried in the infrared heaters, only SEC values for the 6 hour marinating duration were significantly ($p \leq 0.05$) different for the two drying systems.

The specific energy requirements for samples dried under the HWL infrared heater increased with increasing marinating duration. This may be as a consequence of changes in the bonding conditions of water in the food material (Lewicki, 2004), where water was tightly bound as a result of increasing water binders (charged solutes), due to marinade uptake, and hence brought about an overall increase in the energy required to move water out of the product in order for it to reach the target moisture content. On the other hand, the SEC by samples that were dried under the LWL infrared heater reduced, with increasing marinating time, as opposed to observations made for samples that under the HWL infrared heater that had the SEC values increase, with increasing marinating time. High temperature drying increases the

drying rates, as the solute concentration in the food matrix increases (Sabadini *et al.*, 1998). Due to increasingly elevated product temperature, as was the case for samples dried under the LWL infrared heater, the drying rates increased with increasing marinating duration as discussed by Chabbouh *et al.* (2013). Therefore, quicker drying resulted in lesser energy consumption in the case of the HWL infrared heater. This explains the reducing trend in the SEC with increasing marinating duration observed in LWL infrared dried samples.

The difference in the peak emission wavelengths of the two infrared heaters may have also had an effect on the absorption of infrared radiation by the food due to differences in the state of water in the food after being marinated for different durations, with the HWL infrared heater having its radiation being absorbed by the food more efficiently than the LWL infrared heater. This concept of peak absorption bands and efficient absorption of infrared energy at different wavelengths during drying of foods that have different hydration potential has been briefly discussed by Gabel *et al.* (2006).

Kocabiyik and Tezer (2009) in their study where they dried carrot slices using different levels of infrared radiation and air velocities observed that the SEC of the samples lay between 12.22 and 14.58 $MJ.kg^{-1}$. The SEC values reported in the present study are higher than their study due to differences in the dryer design (in their study, there was a drying plenum and a fan to move air over the drying products). Motevali (2011a; 2011b) reported similar results to those observed by Kocabiyik and Tezer (2009). Other studies by Das *et al.* (2004), Afzal *et al.* (1999) and Hebbar *et al.* (2004) reported SEC ranging from 7.6 $MJ.kg^{-1}$ to 73.4 $MJ.kg^{-1}$. The SEC values in the present are within the reported limits but can be reduced further if the natural air convection was substituted with forced hot air convection during the drying process.

### 4.3 Drying Models

The drying models that best explained the moisture loss of biltong dried under different pre-treatment and drying conditions were evaluated based on their coefficient of determination ($R^2$) and root mean square error (RMSE) values as discussed in Section 2.4.5. The models that were selected for evaluation include; the Page Model, Logarithmic Model, Simplified Diffusion (SDF) model, approximation of diffusion model (ADM) and the Midilli Model. The equations of these models and their constants are as described in Table 3.1. A model's drying rate constant (k), is an important model parameter that has a physical relationship with

a product's drying conditions such as the drying temperature and the moisture diffusion characteristics.

Table 4.1 presents a summary of model coefficients, $R^2$ and RMSE values for the five models that were selected and tested using the drying kinetics data of samples dried under the convective air dryer. It is evident that for the 6-hour marinated sample, the approximation of diffusion model (ADM) best fitted the moisture loss data by giving the highest $R^2$ values of 0.9998, 0.9996 and 0.9991 for the 5, 10 and 15 mm slices, respectively and the lowest RMSE values (Table 4.1). The model that fitted the 12-hour marinated samples the closest was the ADM Model, with $R^2$ values of 0.9981, 0.9977 and 0.9983 for the 5, 10 and 15 mm samples, respectively. The 24-hour marinated samples also had the ADM Model performing better than the other models with $R^2$ values ranging from 0.9938 to 0.9996 for all product thicknesses. It can be further deduced from Table 4.1 that the k values of the models generally increased with decreasing product thicknesses for all the models except the Simplified Diffusion Model (SDF) model, for biltong products dried under the convective air drying system. There was also a general decrease in the k values with increasing marinating time. The k values ranged from 0.1294 $hr^{-1}$ to 9.728 x $10^{-7}$ $hr^{-1}$.

The k values in this study are approximately 60 times higher than those of beef jerky processing presented by Thiagarajan *et al.* (2006). These differences may have been due to differences in the drying and pre-processing techniques used in the two studies. The values in the present study are, however, close to those observed by Chabbouh *et al.* (2013) for convective air dried Kaddid.

Table 4.2 presents a summary of model coefficients, $R^2$ and RMSE values for the five models that were selected and tested using the drying kinetics data of the HWL infrared dried samples. The ADM Model best described the results for the infrared drying of the 6-hour marinated samples that were dried under the HWL infrared heater as evidenced by high $R^2$ values, when compared to those of the other models. In this case, the $R^2$ values were 0.9958, 0.9980 and 0.9997 for the 5, 10 and 15 mm thick samples, respectively. It can also be deduced that the ADM Model best described the infrared drying for the 12-hour marinated samples that were dried under the HWL infrared heater since it had the highest $R^2$ values of 0.9996, 0.9995 and 0.9997 for the 5, 10 and 15 mm thick samples, respectively. In addition, the drying data for the 24-hour marinated samples that were dried under this heater fitted best

to the Midilli Model, with the highest $R^2$ values of 0.9973, 0.9990 and 0.9989 for the 5, 10 and 15 mm thick samples, respectively.

Table 4.1 The model coefficients and statistical parameters for the Page, Approximation of diffusion (ADM), Logarithmic, Simplified Diffusion (SDF) Model and the Midilli Model, for various samples that were dried under the convective air dryer

| Marinating duration (hours) | Model | Thickness (mm) | Coefficients | | | | | $R^2$ | RMSE |
|---|---|---|---|---|---|---|---|---|---|
| | | | k ($hr^{-1}$) | n | a | b | c | | |
| 6 | Page | 5 | 0.1294 | 0.8161 | | | | 0.9948 | 0.0302 |
| | | 10 | 0.1122 | 0.7870 | | | | 0.9970 | 0.0226 |
| | | 15 | 0.0936 | 0.7101 | | | | 0.9968 | 0.0212 |
| | ADM | 5 | 0.1262 | | 0.7954 | 0.1456 | | 0.9998 | 0.0064 |
| | | 10 | 0.1187 | | 0.6516 | 0.1949 | | 0.9996 | 0.0089 |
| | | 15 | 0.1008 | | 0.5283 | 0.1481 | | 0.9991 | 0.0124 |
| | Logarithmic | 5 | 0.0987 | | 0.9263 | | 0.060 | 0.9983 | 0.0188 |
| | | 10 | 0.0754 | | 0.9115 | | 0.066 | 0.9979 | 0.0203 |
| | | 15 | 0.0538 | | 0.8342 | | 0.139 | 0.9975 | 0.0203 |
| | Simplified diffusion | 5 | 2.064E-6 | | 0.9724 | | | 0.9902 | 0.0416 |
| | | 10 | 6.142E-6 | | 0.9629 | | | 0.9897 | 0.0419 |
| | | 15 | 7.457E-6 | | 0.9398 | | | 0.9750 | 0.0591 |
| | Midilli | 5 | 0.1251 | 0.8562 | 1.0080 | 0.0005 | | 0.9982 | 0.0209 |
| | | 10 | 0.1065 | 0.8309 | 1.0070 | 0.0004 | | 0.9992 | 0.0135 |
| | | 15 | 0.0829 | 0.7861 | 1.0050 | 0.0008 | | 0.9996 | 0.0071 |
| 12 | Page model | 5 | 0.0886 | 0.8121 | | | | 0.9887 | 0.0435 |
| | | 10 | 0.0746 | 0.7962 | | | | 0.9906 | 0.0384 |
| | | 15 | 0.0717 | 0.7661 | | | | 0.9904 | 0.0372 |
| | ADM | 5 | 0.0712 | | 0.8844 | 0.0360 | | 0.9981 | 0.0192 |
| | | 10 | 0.0647 | | 0.7700 | 0.1269 | | 0.9977 | 0.0203 |
| | | 15 | 0.0637 | | 0.6972 | 0.1303 | | 0.9983 | 0.0168 |
| | Logarithmic | 5 | 0.0686 | | 0.9024 | | 0.094 | 0.9981 | 0.0193 |
| | | 10 | 0.0555 | | 0.8829 | | 0.193 | 0.9973 | 0.0224 |
| | | 15 | 0.0513 | | 0.8500 | | 0.148 | 0.9975 | 0.0204 |
| | Simplified diffusion | 5 | 1.289E-6 | | 0.9762 | | | 0.9828 | 0.0537 |
| | | 10 | 3.819E-6 | | 0.9719 | | | 0.9807 | 0.0552 |
| | | 15 | 7.039E-6 | | 0.9643 | | | 0.9711 | 0.0604 |
| | Midilli | 5 | 0.06565 | 0.9642 | 0.9966 | 0.0010 | | 0.9972 | 0.0254 |
| | | 10 | 0.06073 | 0.9129 | 1.0060 | 0.0010 | | 0.9965 | 0.0277 |
| | | 15 | 0.05886 | 0.8849 | 1.0090 | 0.0011 | | 0.9968 | 0.0255 |
| 24 | Page model | 5 | 0.06776 | 0.8329 | | | | 0.9912 | 0.0378 |
| | | 10 | 0.06737 | 0.8217 | | | | 0.9809 | 0.0552 |
| | | 15 | 0.06268 | 0.7792 | | | | 0.9923 | 0.0326 |
| | ADM | 5 | 0.05224 | | 0.9109 | -0.020 | | 0.9973 | 0.0225 |
| | | 10 | 0.05177 | | 0.9254 | -0.108 | | 0.9938 | 0.0340 |
| | | 15 | 0.04894 | | 0.7974 | 0.0578 | | 0.9996 | 0.0081 |
| | Logarithmic | 5 | 0.05632 | | 0.8984 | | 0.096 | 0.9974 | 0.0223 |
| | | 10 | 0.05215 | | 0.8863 | | 0.122 | 0.9937 | 0.0342 |
| | | 15 | 0.04585 | | 0.8425 | | 0.156 | 0.9995 | 0.0086 |
| | Simplified diffusion | 5 | 9.728E-7 | | 0.9755 | | | 0.9859 | 0.0477 |
| | | 10 | 3.848E-6 | | 0.9825 | | | 0.9737 | 0.0648 |
| | | 15 | 6.264E-6 | | 0.9667 | | | 0.9784 | 0.0546 |
| | Midilli | 5 | 0.04670 | 1.0060 | 0.9903 | 0.0010 | | 0.9972 | 0.0251 |
| | | 10 | 0.04518 | 1.0710 | 0.9937 | 0.0014 | | 0.9941 | 0.0363 |
| | | 15 | 0.03898 | 0.9296 | 1.0040 | 0.0013 | | 0.9992 | 0.0124 |

Table 4.2 The model coefficients and statistical parameters for the Page, Approximation of diffusion (ADM), Logarithmic, Simplified Diffusion (SDF) Model and the Midilli Model, for various samples that were dried under the high wavelength (HWL) infrared heater

| Marinating duration (hours) | Model | Thickness (mm) | Coefficients | | | | | $R^2$ | RMSE |
|---|---|---|---|---|---|---|---|---|---|
| | | | k ($hr^{-1}$) | n | a | b | c | | |
| 6 | Page | 5 | 0.3040 | 0.8780 | | | | 0.9914 | 0.0300 |
| | | 10 | 0.2400 | 0.7846 | | | | 0.9886 | 0.0324 |
| | | 15 | 0.1644 | 0.7692 | | | | 0.9956 | 0.0171 |
| | ADM | 5 | 0.3418 | | 3.6940 | 0.9974 | | 0.9958 | 0.0408 |
| | | 10 | 0.2643 | | 0.6075 | 0.1716 | | 0.9980 | 0.0142 |
| | | 15 | 0.2933 | | 0.4296 | 0.1622 | | 0.9997 | 0.0050 |
| | Logarithmic | 5 | 0.1218 | | 0.9191 | | 0.099 | 0.9984 | 0.0138 |
| | | 10 | 0.2504 | | 0.8453 | | 0.156 | 0.9957 | 0.0210 |
| | | 15 | 0.1784 | | 0.7552 | | 0.237 | 0.9980 | 0.0121 |
| | Simplified diffusion | 5 | 6.508E-6 | | 0.9860 | | | 0.9862 | 0.0379 |
| | | 10 | 1.588E-5 | | 0.9565 | | | 0.9724 | 0.0505 |
| | | 15 | 2.132E-5 | | 0.9445 | | | 0.9749 | 0.0407 |
| | Midilli | 5 | 0.3044 | 0.9905 | 1.0130 | 0.0073 | | 0.9977 | 0.0175 |
| | | 10 | 0.2324 | 0.9069 | 1.0160 | 0.0066 | | 0.9947 | 0.0246 |
| | | 15 | 0.1662 | 0.8574 | 1.0090 | 0.0064 | | 0.9987 | 0.0102 |
| 12 | Page model | 5 | 0.2607 | 0.7828 | | | | 0.9890 | 0.0302 |
| | | 10 | 0.2154 | 0.7599 | | | | 0.9951 | 0.0189 |
| | | 15 | 0.1800 | 0.7436 | | | | 0.9958 | 0.0163 |
| | ADM | 5 | 0.3387 | | 0.3917 | 0.0159 | | 0.9996 | 0.0052 |
| | | 10 | 0.3296 | | 0.5050 | 0.1829 | | 0.9995 | 0.0063 |
| | | 15 | 0.0235 | | 0.0917 | 0.1287 | | 0.9997 | 0.0027 |
| | Logarithmic | 5 | 0.1994 | | 0.7803 | | 0.201 | 0.9951 | 0.0181 |
| | | 10 | 0.1685 | | 0.8282 | | 0.156 | 0.9963 | 0.0169 |
| | | 15 | 0.0589 | | 0.7170 | | 0.277 | 0.9991 | 0.0050 |
| | Simplified diffusion | 5 | 4.412E-6 | | 0.9529 | | | 0.9719 | 0.0482 |
| | | 10 | 1.276E-5 | | 0.9339 | | | 0.9729 | 0.0445 |
| | | 15 | 2.176E-5 | | 0.9283 | | | 0.9693 | 0.0438 |
| | Midilli | 5 | 0.2545 | 0.8842 | 1.0170 | 0.0051 | | 0.9982 | 0.0132 |
| | | 10 | 0.2167 | 0.8182 | 1.0150 | 0.0036 | | 0.9984 | 0.0115 |
| | | 15 | 0.1837 | 0.7920 | 1.0140 | 0.0035 | | 0.9982 | 0.0114 |
| 24 | Page model | 5 | 0.0952 | 0.8662 | | | | 0.9881 | 0.0282 |
| | | 10 | 0.0650 | 0.8825 | | | | 0.9954 | 0.0164 |
| | | 15 | 0.0461 | 0.8796 | | | | 0.9982 | 0.0082 |
| | ADM | 5 | 0.0913 | | 0.9481 | -0.622 | | 0.9962 | 0.0167 |
| | | 10 | 0.0586 | | 0.9709 | -0.990 | | 0.9990 | 0.0080 |
| | | 15 | 0.0774 | | 0.4065 | 0.1965 | | 0.9987 | 0.0071 |
| | Logarithmic | 5 | 0.1225 | | 0.7727 | | 0.246 | 0.9969 | 0.0152 |
| | | 10 | 0.0759 | | 0.7741 | | 0.231 | 0.9988 | 0.0088 |
| | | 15 | 0.0526 | | 0.7277 | | 0.269 | 0.9988 | 0.0070 |
| | Simplified diffusion | 5 | 1.698E-6 | | 0.9817 | | | 0.9801 | 0.0364 |
| | | 10 | 4.639E-6 | | 0.9832 | | | 0.9905 | 0.0236 |
| | | 15 | 7.175E-6 | | 0.9836 | | | 0.9943 | 0.0145 |
| | Midilli | 5 | 0.0896 | 1.0520 | 1.0070 | 0.0098 | | 0.9973 | 0.0147 |
| | | 10 | 0.0599 | 1.0220 | 1.0010 | 0.0059 | | 0.9990 | 0.0083 |
| | | 15 | 0.0452 | 0.9590 | 0.9995 | 0.0037 | | 0.9989 | 0.0071 |

The k values in Table 4.2 range from 1.698 x $10^{-6}$ $hr^{-1}$to 0.3418 $hr^{-1}$ and it decreases with increasing product thicknesses for all the models except the SFD Model. Increasing the product marinating duration resulted in a decrease in the k values for all the models assayed and for samples of all thicknesses dried under the HWL infrared heater.

Table 4.3 presents a summary of model coefficients, $R^2$ values and RMSE values for the five models that were selected and tested using the drying kinetics data of the LWL infrared dried samples. In this case, the model fits to the moisture loss data of the LWL infrared dried samples depicted a general increase in the k values with increasing marinating time for all slice thicknesses. These k values range from 8.924 x $10^{-6}$ $hr^{-1}$ to 0.7700 $hr^{-1}$. This is consistent with the higher drying rates observed for samples dried under this dryer, as these k values are higher than those of convective air and HWL infrared dried samples.

It can be clearly seen in Table 4.3 that the ADM Model best fitted the data of the samples that were marinated for six hours before being dried under the LWL infrared heater since it had the highest $R^2$ values when compared to the other models. The $R^2$ values were, in this case, 0.9998, 0.9993 and 0.9994 for the 5, 10 and 15 mm thick samples, respectively. The ADM model also had the best fits for the drying data of samples that were marinated for 12 hours by giving the highest $R^2$ values amongst the models tested. These model $R^2$ values were, 0.9998, 0.9995 and 0.9997 for the 5, 10 and 15 mm thick samples, respectively. The Midilli Model gave the highest $R^2$ values for the 24-hour marinated biltong samples that were dried under the LWL infrared heater compared to the other models tested for the same marinating time with $R^2$ values of 0.9994, 0.9992 and 0.9995 for the 5, 10 and 15 mm thick samples, respectively. The k values of all the models except the SFD Model, generally decreased with increasing sample thicknesses (Table 4.3). This may be due to the fact that, as the slice thickness increased, the resistance to infrared penetration of the products increased, hence a reduction in the k values as thickness increased. Based on these results, it can be concluded that the ADM Model, therefore, best describes the infrared drying of biltong under the given experimental conditions. The ADM Model is also the best for convective air drying of biltong as it gave the best fits for the 12- and 24-hour marinated samples. The ADM Model also gave reasonably good fits for the convective air drying of biltong products that had previously been marinated for 6 hours.

Table 4.3 The model coefficients and statistical parameters for the Page Model, Approximation of diffusion (ADM), Logarithmic, Simplified Diffusion (SDF) Model and the Midilli model, for various samples that were dried under the low wavelength (LWL) infrared heater

| Marinating duration (hours) | Model | Thickness (mm) | Coefficients | | | | | $R^2$ | RMSE |
|---|---|---|---|---|---|---|---|---|---|
| | | | k ($hr^{-1}$) | n | a | b | c | | |
| 6 | Page | 5 | 0.4702 | 0.7911 | | | | 0.9975 | 0.0139 |
| | | 10 | 0.3506 | 0.8095 | | | | 0.9971 | 0.0151 |
| | | 15 | 0.3033 | 0.7980 | | | | 0.9980 | 0.0114 |
| | ADM | 5 | 0.6469 | | 0.5536 | 0.2348 | | 0.9998 | 0.0044 |
| | | 10 | 0.4138 | | 0.4580 | 0.2359 | | 0.9993 | 0.0081 |
| | | 15 | 0.2977 | | 0.3420 | 0.2031 | | 0.9994 | 0.0066 |
| | Logarithmic | 5 | 0.5166 | | 0.8690 | | 0.121 | 0.9986 | 0.0117 |
| | | 10 | 0.4246 | | 0.8455 | | 0.149 | 0.9980 | 0.0133 |
| | | 15 | 0.3566 | | 0.7956 | | 0.196 | 0.9981 | 0.0118 |
| | Simplified diffusion | 5 | 8.92E-6 | | 0.9472 | | | 0.9835 | 0.0381 |
| | | 10 | 2.82E-5 | | 0.9537 | | | 0.9847 | 0.0349 |
| | | 15 | 4.91E-5 | | 0.9515 | | | 0.9845 | 0.0320 |
| | Midilli | 5 | 0.4786 | 0.8722 | 1.0030 | 0.0088 | | 0.9994 | 0.0080 |
| | | 10 | 0.3846 | 0.8837 | 0.0095 | 1.0060 | | 0.9985 | 0.0123 |
| | | 15 | 0.3132 | 0.8675 | 1.0040 | 0.0098 | | 0.9990 | 0.0092 |
| 12 | Page model | 5 | 0.5199 | 0.7181 | | | | 0.9892 | 0.0281 |
| | | 10 | 0.3736 | 0.8915 | | | | 0.9983 | 0.0112 |
| | | 15 | 0.3237 | 0.8327 | | | | 0.9960 | 0.0158 |
| | ADM | 5 | 0.7547 | | 0.7207 | 0.0912 | | 0.9989 | 0.0095 |
| | | 10 | 0.4505 | | 0.7248 | 0.2409 | | 0.9995 | 0.0063 |
| | | 15 | 0.3980 | | 0.8170 | -0.012 | | 0.9997 | 0.0048 |
| | Logarithmic | 5 | 0.6700 | | 0.8148 | | 0.188 | 0.9985 | 0.0110 |
| | | 10 | 0.4950 | | 0.8891 | | 0.112 | 0.9995 | 0.0067 |
| | | 15 | 0.4059 | | 0.8109 | | 0.193 | 0.9997 | 0.0046 |
| | Simplified diffusion | 5 | 9.23E-6 | | 0.9341 | | | 0.9577 | 0.0558 |
| | | 10 | 3.04E-5 | | 0.9787 | | | 0.9945 | 0.0203 |
| | | 15 | 5.76E-5 | | 0.9662 | | | 0.9860 | 0.0297 |
| | Midilli | 5 | 0.5487 | 0.9029 | 1.0060 | 0.0230 | | 0.9976 | 0.0150 |
| | | 10 | 0.3909 | 0.9672 | 1.0040 | 0.0107 | | 0.9994 | 0.0075 |
| | | 15 | 0.3411 | 0.9777 | 1.0030 | 0.0209 | | 0.9996 | 0.0058 |
| 24 | Page model | 5 | 0.5815 | 0.8903 | | | | 0.9970 | 0.0169 |
| | | 10 | 0.4030 | 0.8954 | | | | 0.9915 | 0.0266 |
| | | 15 | 0.3808 | 0.9283 | | | | 0.9923 | 0.0234 |
| | ADM | 5 | 0.7700 | | 0.9276 | 0.0190 | | 0.9994 | 0.0078 |
| | | 10 | 0.6924 | | 0.9833 | 0.7203 | | 0.9980 | 0.0136 |
| | | 15 | 0.6845 | | 0.9978 | 2.0020 | | 0.9978 | 0.0134 |
| | Logarithmic | 5 | 0.6978 | | 0.9263 | | 0.079 | 0.9994 | 0.0089 |
| | | 10 | 0.5924 | | 0.8953 | | 0.124 | 0.9979 | 0.0139 |
| | | 15 | 0.4811 | | 0.8783 | | 0.144 | 0.9975 | 0.0143 |
| | Simplified diffusion | 5 | 1.31E-5 | | 0.9822 | | | 0.9935 | 0.0251 |
| | | 10 | 3.58E-5 | | 0.9870 | | | 0.9874 | 0.0323 |
| | | 15 | 6.22E-5 | | 0.9952 | | | 0.9902 | 0.0264 |
| | Midilli | 5 | 0.6041 | 1.0010 | 1.0030 | 0.0139 | | 0.9994 | 0.0088 |
| | | 10 | 0.4182 | 1.0892 | 1.0050 | 0.0222 | | 0.9992 | 0.0090 |
| | | 15 | 0.3873 | 1.1323 | 1.0050 | 0.0265 | | 0.9995 | 0.0065 |

It can be observed from Table 4.1, 4.2 and 4.3 that there is a general increase in the model drying rate constant (k), in the order, k for LWL infrared dried biltong >k for HWL infrared dried biltong >k for convective air dried biltong. The average k values for the LWL infrared heater, HWL infrared heater and the convective air dryer were 0.3728 $hr^{-1}$, 0.1371 $hr^{-1}$ and 0.0590 $hr^{-1}$, respectively.

Comparison of the models' drying constant (k) and the product average drying rates depict higher k values as compared to the average drying rate. This trend was true for all the models. Figure 4.21 shows the model fits of the 5 mm thick, HWL infrared dried samples that had been previously marinated for 12 hours.

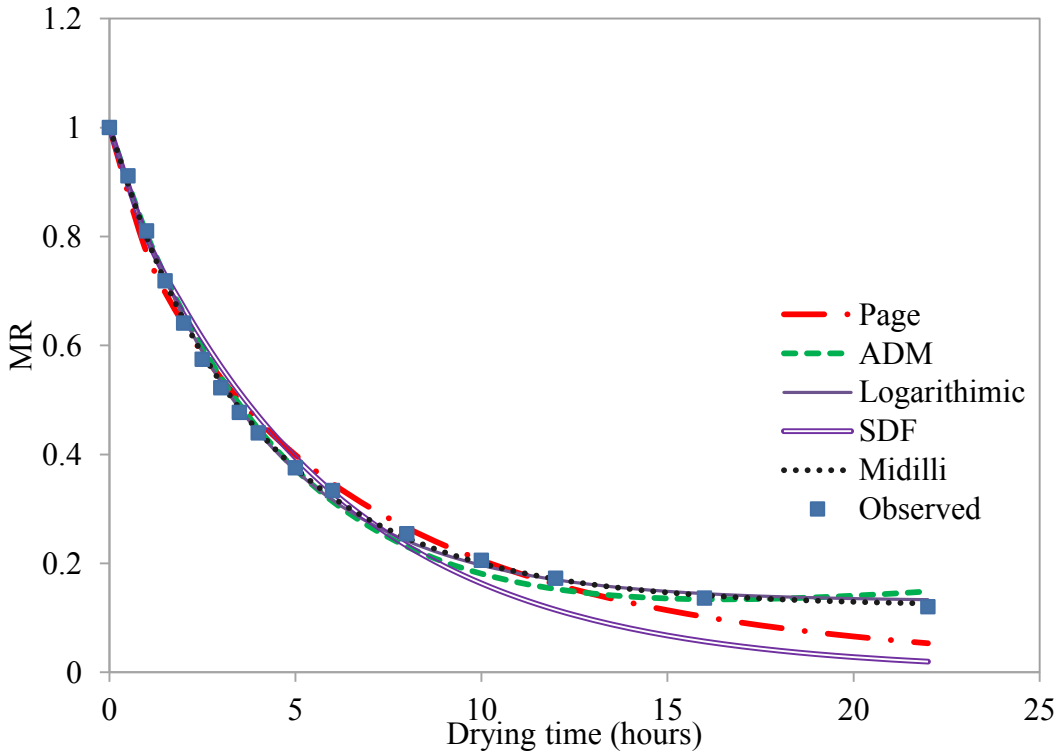


Figure 4.21 Model fits in comparison to the observed values, for various Models that were fitted to the moisture loss data of the 5 mm thick, 12-hour marinated HWL infrared dried samples

It can be seen from Figure 4.21 that the models, generally fitted well to the data, with Page and the SDF Models underestimating the product moisture content towards the end of the drying period. Drying models fall into two categories namely the theoretical, and semi-theoretical and empirical models. Theoretical models consider the internal moisture transfer while the semi-theoretical and empirical models only consider the external moisture transfer between the product and surrounding air (Özdemir and Onur Devres, 1999; Lahsasni *et al.*,

2004). The SDF Model is a simplified theoretical model. It takes into account the internal moisture transfer characteristics of the product. The limiting factor during the drying process in the present study was the external moisture transfer process. The ADM Model falls into the second category (semi-theoretical and empirical) and for this reason, its performance in predicting the external moisture transfer from the products may have been better than the other models as evidenced by the high $R^2$ values and low RMSE in most of biltong products that underwent different pre-drying treatments.

The product temperatures in the study by Thiagarajan *et al.* (2006) compares well to those of biltong in this study. They, however, found the Page Model to be best at explaining the thin layer drying of jerky. In a similar study where kaddid, a traditional cured beef snack in Tunisia was dried by Chabbouh *et al.* (2013) in a convective air dryer, it was observed that the drying data fitted best to the ADM Model with k values ranging from 0.302 to 1.218 $hr^{-1}$ for un-spiced and spiced kaddid respectively. This observation is consistent with those made in the present study. However, the slight differences in the k values reported in their study and those of the present research may be attributed to differences in the experimental conditions, the spicing method and differences in the drying temperatures.

## 4.4 Quality Attributes

### 4.4.1 Colour

**Fresh and marinated colour parameters**

Fresh beef slices had lightness (L*) values ranging from 42.08 to 47.41, redness (a*) values ranging from 22.75 to 26.07 and yellowness values (b*) ranging from 19.29 to 20.03. Marinated beef samples had lightness (L*) values ranging from 31.51 to 33.58, redness (a*) values ranging from 12.76 to 16.08 and yellowness values (b*) ranging from 20.79 to 24.74. Additional data is presented in Appendix F depicting detailed information on the specific sample colour attributes of the samples before marinating, after marinating and after drying for different samples and drying conditions. The trends in the sample colour attributes for each of these stages during processing of biltong will be discussed in detail in the last topic of Section 4.4.1.

**Colour parameters for dried samples**

Table 4.4 presents the colour parameters of the dry samples, and the total colour difference (ΔE), calculated using the colour attributes of marinated and dry samples.

Table 4.4 The L* a* b* colour parameters and calculated total colour difference (ΔE) of samples of various thickness and marinating durations that were dried under the convective air dryer, high wavelength (HWL) and low wavelength (LWL) infrared heating systems

| Drying system | Pre-treatments | | Colour parameters | | | |
|---|---|---|---|---|---|---|
| | Marinating time (hours) | Thickness (mm) | L* | a* | b* | ΔE |
| Convective air dryer | 6 | 5 | 32.05±0.93$^{a}$ | 11.11±1.42$^{ab}$ | 14.83±1.26$^{ab}$ | 11.96±0.45$^{f}$ |
| | | 10 | 27.72±0.74$^{bc}$ | 9.57±1.23$^{b}$ | 12.31±0.96$^{bc}$ | 8.69±0.89$^{gh}$ |
| | | 15 | 22.73±0.43$^{e}$ | 5.20±0.97$^{e}$ | 6.07±1.24$^{e}$ | 13.17±0.76$^{f}$ |
| | 12 | 5 | 27.24±0.86$^{c}$ | 10.16±1.22$^{ab}$ | 11.11±1.09$^{c}$ | 21.81±1.23$^{ab}$ |
| | | 10 | 22.38±0.61$^{e}$ | 8.47±1.13$^{bc}$ | 8.69±0.90$^{cd}$ | 17.36±0.83$^{d}$ |
| | | 15 | 21.63±0.75$^{fg}$ | 5.10±1.28$^{e}$ | 7.43±1.20$^{d}$ | 18.19±0.68$^{cd}$ |
| | 24 | 5 | 29.01±0.88$^{b}$ | 12.04±1.31$^{ab}$ | 13.13±1.28$^{bc}$ | 13.10±0.91$^{f}$ |
| | | 10 | 25.87±0.94$^{cd}$ | 10.95±1.56$^{ab}$ | 16.24±1.34$^{ab}$ | 3.87±0.35$^{i}$ |
| | | 15 | 23.32±0.70$^{de}$ | 9.32±1.26$^{c}$ | 11.99±1.03$^{bc}$ | 7.21±1.03$^{h}$ |
| HWL Infrared heater | 6 | 5 | 27.68±1.24$^{bc}$ | 11.86±1.34$^{ab}$ | 16.82±1.32$^{a}$ | 3.64±0.65$^{i}$ |
| | | 10 | 25.92±0.94$^{cd}$ | 9.32±0.72$^{c}$ | 12.80±0.89$^{bc}$ | 12.18±0.82$^{f}$ |
| | | 15 | 22.66±0.51$^{e}$ | 6.84±0.97$^{ce}$ | 8.25±0.64$^{d}$ | 16.47±0.71$^{de}$ |
| | 12 | 5 | 22.90±1.37$^{de}$ | 6.86±1.06$^{ce}$ | 10.00±1.31$^{c}$ | 9.85±0.49$^{g}$ |
| | | 10 | 22.10±0.95$^{e}$ | 6.66±0.93$^{e}$ | 10.53±0.77$^{c}$ | 13.27±0.99$^{f}$ |
| | | 15 | 20.67±0.72$^{g}$ | 5.57±0.84$^{e}$ | 9.10±0.83$^{cd}$ | 18.78±0.72$^{cd}$ |
| | 24 | 5 | 27.02±1.23$^{bc}$ | 9.95±1.33$^{ac}$ | 14.29±1.02$^{b}$ | 9.89±0.58$^{g}$ |
| | | 10 | 23.44±1.16$^{de}$ | 7.70±0.91$^{cde}$ | 9.66±1.45$^{c}$ | 15.35±0.97$^{e}$ |
| | | 15 | 21.18±0.59$^{g}$ | 5.82±0.79$^{e}$ | 6.85±0.92$^{de}$ | 23.04±1.10$^{b}$ |
| LWL Infrared heater | 6 | 5 | 24.87±0.76$^{d}$ | 11.90±0.82$^{a}$ | 13.63±1.09$^{b}$ | 30.51±0.90$^{a}$ |
| | | 10 | 20.83±0.87$^{g}$ | 8.10±0.77$^{cd}$ | 8.92±0.96$^{d}$ | 29.61±0.85$^{a}$ |
| | | 15 | 19.03±0.49$^{h}$ | 6.31±0.78$^{e}$ | 5.87±0.94$^{e}$ | 20.73±0.74$^{b}$ |
| | 12 | 5 | 21.53±0.93$^{fg}$ | 7.65±0.75$^{cd}$ | 10.02±0.81$^{c}$ | 19.12±0.77$^{c}$ |
| | | 10 | 20.24±0.62$^{g}$ | 8.54±0.55$^{c}$ | 7.80±0.89$^{d}$ | 18.78±0.80$^{cd}$ |
| | | 15 | 16.83±0.58$^{i}$ | 6.54±0.85$^{e}$ | 5.52±0.74$^{e}$ | 13.27±0.95$^{f}$ |
| | 24 | 5 | 22.00±1.01$^{efg}$ | 9.62±0.81$^{bc}$ | 9.42±0.72$^{c}$ | 20.95±0.58$^{b}$ |
| | | 10 | 20.48±0.63$^{g}$ | 8.43±0.71$^{c}$ | 6.83±0.91$^{de}$ | 20.12±0.69$^{bc}$ |
| | | 15 | 20.25±0.74$^{g}$ | 8.64±0.82$^{c}$ | 7.82±0.67$^{d}$ | 15.21±0.71$^{e}$ |

Means in the same column with different letters indicate a significant difference ($p \leq 0.05$).

**Lightness (L*)**

The lightness index (L*), indicates the lightness or darkness of a food sample as discussed in Section 2.5.1. An increase in L* values indicate increasing sample lightness and low L* values represent darker foods. The lightness (L*) values of the dried biltong slices ranged from 16.83 to 32.05 (Table 4.4). The Lightness values decreased with increasing product thickness for all the drying systems assayed. The L* values also decreased when the marinating duration was increased from 6 hours to 12 hours, but increased when the marinating duration was increased from 12 hours to 24 hours. This was true for all slice thicknesses for the three drying systems. The L* values were also lower for samples that were dried under the LWL infrared heater when compared to those dried under the HWL infrared heater and the convective air dryer.

Increasing marinating time led to an increase in spice uptake and hence the darker product. Darkening in food samples during drying may have been caused by non-enzymatic browning (Maskan, 2000) with the product temperature being the major controlling factor. Higher drying temperatures may have increased the occurrence of non-enzymatic browning as evidenced by the LWL infrared heater producing the darkest products. Comparison of the L* values for samples that were dried under the two infrared dryers show that the HWL infrared heater had its values closer to those of the convective air dried samples than those dried under the LWL infrared heater. Nindo *et al.* (2003) observed that the L* values of dried asparagus, using different methods, generally decreased with increasing temperature. This observation is consistent with observations made by Sharma and Prasad (2001) in their study where they dried garlic in a microwave dryer under different temperatures.

An increase in product thickness may imply an increase in the capacity for spice uptake hence the decrease in the lightness values with increasing product thickness under the given experimental conditions. Dvořák *et al.* (2007) investigated the colour changes of pheasant meat when exposed to ionizing radiation. The reduction in the L* values for all radiation doses (2.5 to 5 kGy) were found not to be significant. The L* values however reduced with increasing radiation. The reported values ranged from 46.47 to 41.19. The study did not, however, indicate the illuminant that was used, therefore making comparison of the findings of this study to other studies difficult. Thiagarajan *et al.* (2006) in their study where beef jerky was dried in a combined hot air microwave dryer observed that the L* values of the dried jerky decreased with increasing salt level for the 1.28 to 2.28% w/w range, and

increased with further increase in the salt level (from 2.28 to 3.28% w/w). The lightness values reported by Thiagarajan *et al.* (2006) ranged from 36.25 to 25.95 and are close to those of convective air dried biltong products reported in the present study.

A three-factor ANOVA conducted to establish the effect of product thickness, marinating level and the drying system on the L* values showed significant ($p \leq 0.05$) differences between the L* values of the drying systems. LSD tests showed that the L* values of samples dried under the LWL infrared heater were significantly different from those dried under the convective air dryer and HWL infrared heater. The L* values of samples dried under the HWL infrared heater were not significantly different from those dried under the convective air dryer. The product thickness also had a significant ($p \leq 0.05$) effect on the L* values of the samples. The L* values of the 15 mm thick samples were also significantly different from those of both the 10 and 5 mm thick slices. The L* values of the 5 mm thick slices were not significantly different from those of 10 mm thick slices. The marinating duration had no significant ($p \geq 0.05$) effect on the L* values of the dried biltong products. In addition, the interaction between the drying system and the product thickness or the marinating duration, as well as between the product thickness and the marinating duration was not statistically significant ($p \geq 0.05$) for the L* values. The three-way interaction between the drying system, product thickness and the marinating duration was also statistically not significant ($p \geq 0.05$).

The 5 mm thick slices that were marinated for 6 hours and dried under the convective air dryer had the highest L* values. The 15 mm thick biltong slices that were marinated for 12 hours and dried under the LWL infrared heater had the lowest L* values.

**The a* Colour parameter**

The redness (a*) colour values indicates the degree of redness of a food sample as discussed in Section 2.5.1. The redness values of dry samples for different pre-treatment and drying systems ranged from 5.10 to 12.04 (Table 4.4). These values decreased with increasing product thickness for the three drying systems assayed. The a* values were generally higher for the convective air dried samples when compared to those dried under the infrared heaters for all marinating times and thicknesses.

Increasing marinating time generally decreased the redness for all product thicknesses and in all drying systems tested. This trend was also observed by Thiagarajan *et al.* (2006) when they dried jerky in a microwave dryer. It is known that the colour intensity of meat and its

general visual appearance is influenced by the relative proportions of oxymyoglobin (bright red), myoglobin (dark red), and metmyoglobin (grey-brown) in the products (Carlez et al., 1995). Product temperature also plays an important role in colour changes during processing of meat products (Carlez et al., 1995). Therefore, the drying temperature and pre-treatments clearly had an effect on the relative proportions of these compounds in biltong, resulting in changes in the redness colour value. Fisher et al., (2000) reported the a* values of processed ostrich meat to be 11.71 and 11.49, respectively, when 0.15% and 0.30% phosphate was added to the meat. Their values are generally higher than those reported in the present study. This may be due to differences in the biochemical composition of the meat products used in the two studies, and the set-up general of the experiments in the studies.

Statistical analysis of a* values showed that there was no significant ($p \geq 0.05$) difference between the a* values of biltong products processed in different drying systems or products marinated to different degrees. The product thickness however had a significant effect ($p \leq 0.05$) on the a* values of the dried biltong slices. There were significant differences between the a* values of the 5 and 15 mm thick biltong products. There were no significant difference between a* colour values of the 10 and 5 mm thick slices. Redness values of the 10 and 15 mm thick slices were not significantly different. The interaction between the drying system and the product thickness or the marinating duration, as well as between the product thickness and the marinating duration was not statistically significant ($p \geq 0.05$) for the a* values. The three-way interaction between the drying system, product thickness and the marinating duration was also statistically not significant ($p \geq 0.05$).

The 5 mm thick biltong slices that were marinated for 6 hours and dried under the LWL infrared heater had the highest a* colour values while the 15 mm thick slices that were marinated for 6 hours and dried under the convective air dryer had the lowest a* colour values.

**b* Colour parameter**

The b* colour values of food products indicate their degree of yellowness as discussed in Section 2.5.1. It can be observed from Table 4.4 that the b* values of dry biltong processed under different drying systems and pre-treatment conditions ranged from 5.52 to 14.83. The b* values were generally higher for samples dried under the convective air dryer compared to those dried under both the HWL and LWL infrared heaters, for all marinating times and product thicknesses.

The changes in the b* colour values with product thickness, marinating duration and drying system generally followed the trend observed for changes in the a* colour parameter with these treatments. This is consistent with observations made by Thiagarajan *et al.* (2006) and therefore implies that product pre-treatment and drying conditions affected the a* and b* colour values in a similar way, when the trends of both the a* and b* colour values are matched, although not in a quantitative respect.

Statistical analysis showed that there were no significant ($p \geq 0.05$) differences between the b* values of biltong treated to different marinating levels. There were, however, significant ($p \leq 0.05$) differences in the b* colour values between biltong slices dried under different drying systems. There was a significant difference between the b* values of biltong slices dried under the convective air dryer and those dried under the LWL infrared heater, as well as between those dried under the HWL infrared heater and LWL infrared heater. The b* values of biltong samples dried under the HWL infrared heater were not significantly different from those dried under the convective air dryer. There were also significant differences ($p \leq 0.05$) in the b* values for biltong slices of different thicknesses, with those of 15 and 5 mm thick slices, as well as between those of 10 and 15 mm thick being significantly different. There were no significant differences in the b* colour values between biltong slices of 10 and 5 mm thickness. The interaction between the drying system and the product thickness or the marinating duration, as well as between the product thickness and the marinating duration was not statistically significant ($p \geq 0.05$) for the b* values. The three-way interaction between the drying system, product thickness and the marinating duration was also statistically not significant ($p \geq 0.05$).

The highest b* values came from the 5 mm thick samples that were marinated for 6 hours and dried under the HWL infrared heater, while the lowest b* values came from 15 mm thick samples that were marinated for 12 hours and dried under the LWL infrared heater.

**Total colour difference (ΔE)**

The total colour difference (ΔE) of food products is a ua ntitative indicator of colour changes that occurred due to a processing step as discussed in Section 2.5. . Increasing values of ΔE indicate increasing colour changes in the product. The ΔE values in the forthcoming discussion signify total colour difference between marinated and that of biltong dried under different drying systems and pre-treatment conditions. The ΔE values for the samples, had a range of 3.64 to 30.51 (see Table 4.4).

It is evident from Table 4.4 that there is a decrease in ΔE values with an increase in product thickness from the 5 mm thick slices to 10 mm thick slices, and subse uent increase in ΔE values from the 10 mm thick slices to the 15 mm thick slices for all marinating durations, for samples that were dried under the convective dryer. The ΔE values of biltong dried under the HWL infrared heater increased with increasing product thicknesses for all marinating times. However, samples that were dried under the LWL infrared heater had decreasing ΔE values with increasing product thicknesses for all marinating durations.

The ΔE values of the dry biltong slices for different marinating durations dried under the LWL infrared heater generally followed the trend reported by Thiagarajan *et al.* (2006). The ΔE values of the dry biltong slices of different marinating durations dried under the convective dryer and the HWL infrared heater did not follow this trend. In addition, biltong slices dried under the LWL infrared heater had the highest ΔE values for all marinating durations and product thicknesses. This was expected as ΔE values generally increase in food products with increasing processing temperature (Maskan, 2001b; Nindo *et al.*, 2003).

Statistical analysis showed that there was significant ($p \leq 0.05$) difference between ΔE values of samples that were dried under different drying systems. There were significant differences between the ΔE values of samples that were dried under the convective dryer and the LWL infrared, heater as well as those that were dried under the HWL infrared heater and LWL infrared heater. There were however no significant difference in the ΔE values between samples that were dried under the convective air dryer and the HWL infrared heater. Biltong slices marinated for different durations showed no significant ($p \geq 0.05$) difference in their ΔE values. The thickness of the biltong slices also had no significant ($p \geq 0.05$) effect on the ΔE values. There was a significant ($p \leq 0.05$) interaction between the drying system used and the marinating duration, as well as between the drying system and the slice thickness. There was also a significant ($p \leq 0.05$) interaction between the drying system, marinating duration and the product thickness. There was however no significant ($p \geq 0.05$) interaction in the ΔE values between the marinating duration and the product thickness. This implies that the effect of the drying system on ΔE over all levels of the marinating duration or the product thickness was different averaging over levels of the product thickness or marinating duration, respectively.

The 5 mm thick slices marinated for 6 hours and dried under the LWL infrared heater had the highest ΔE values, while those with a thickness of 5 mm that had been marinated for 6 hours and dried in the HWL infrared heater had the lowest ΔE values.

**Trends in colour attributes for fresh, marinated and dry samples**

The marinating process caused a decrease in the lightness (L*) values of fresh beef samples regardless of their thickness or marinating duration. A further decrease in lightness was observed when marinated beef samples were dried. Therefore, the dry samples had lower lightness values compared to the marinated and fresh beef slices. This observation was true for all samples regardless of their thickness, marinating duration or the drying system used to dry the products.

Fresh beef samples also had the highest redness (a*) values and this decrease during the marinating process. This trend was observed for all samples regardless of their thickness or marinating duration. A further decrease in redness was observed when marinated beef samples were dried. The dry biltong slices, therefore, had lower redness values compared to those of the fresh and marinated beef slices. This trend was true for all biltong slices regardless of the marinating duration, their thickness or the drying system used to dry the samples.

The yellowness (b*) of beef slices generally increased during the marinating process and decreased when the marinated beef slices were dried, with the yellowness values increasing in 85% of the samples after the marinating process. This behaviour was true for all samples regardless of their marinating duration, thickness or the drying system that was used to dry the samples. There was a general reduction in the yellowness values after marinated samples were dried regardless of the drying system used, the product thickness or the marinating level.

The behaviour of ΔE values, calculated between the fresh and marinated beef slices is depicted graphically in Figure 4.22. It can be seen that there is an increase in ΔE when the marinating duration is doubled from  to  2  hours for all thickness and a decrease in the ΔE values when the marinating duration is further doubled from 12 to 24 hours (Figure 4.22). The 10 mm thick beef slices had the highest total colour difference after the marinating process.

Graphical presentations in Appendix F depicts the behavioural characteristics of the fresh, marinated and dried samples' colour attributes, under different pre-treatment and drying conditions.

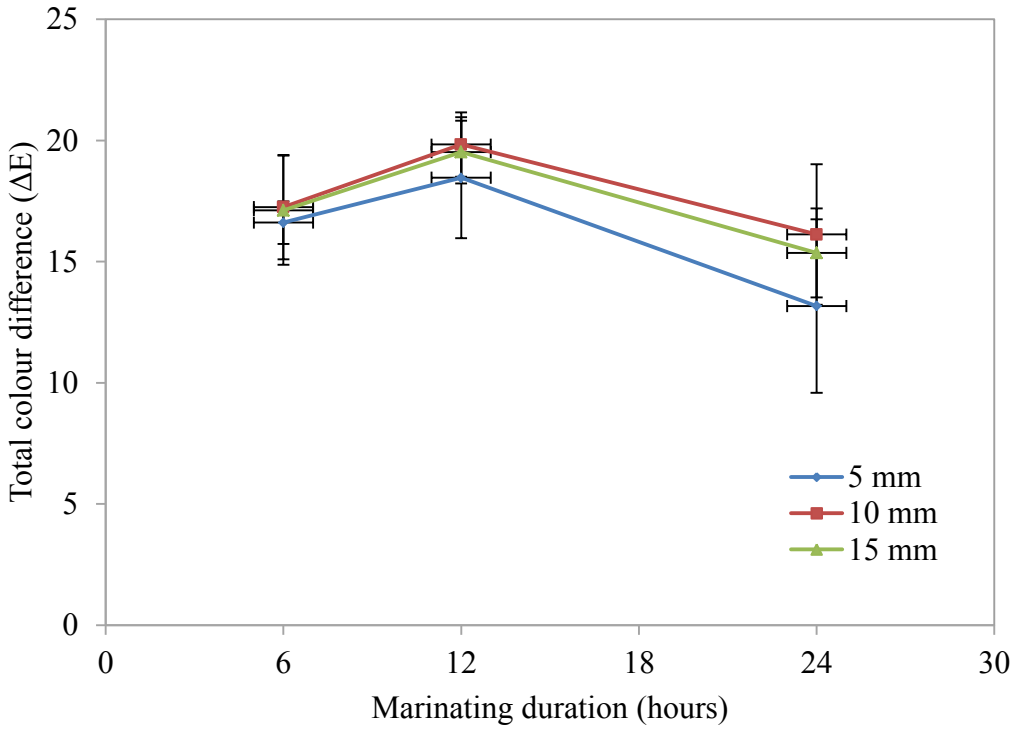


Figure 4.22 Variations in the total colour difference (calculated between fresh and marinated biltong samples), with product thickness and marinating duration

### 4.4.2 Textural characteristics

The textural characteristics of dry biltong slices, and the changes thereof under different drying systems and pre-treatment conditions are presented and discussed in this section. These characteristics include the peak puncture force required for a 3.1 mm cylindrical probe to completely pierce through the samples and texture profile analysis where the samples were subjected to two successive bites (mimic mastication) using a warner bratzlier probe.

**Puncture values**

The maximum force (peak force) required to completely puncture through a dry biltong sample were measured and the results are presented in Table 4.5. The maximum force (peak force) that punctured the dry samples ranged from 12.27 N to 131.33 N.

It can be observed in Table 4.5 that the peak puncture force required for the dry samples increased with increasing product thicknesses for all marinating durations and drying systems tested. The 15 mm thick biltong slices recorded the highest peak puncture force for each

marinating period while the 5 mm thick slices recorded the lowest peak puncture force for each marinating duration. The 15 mm thick samples were in this case, harder to penetrate than the 5 and 10 mm thick samples hence requiring the high forces that were observed. This trend is expected since an increase in product thickness means more muscle and myofibril fibres that have to fail during the test as the probe is forced through the sample and hence a higher force is required to sever these fibres.

Increasing marinating periods also resulted in an increase in the peak puncture force for samples dried under the same dryer (Table 4.5). This is true within each drying system tested and for all product thicknesses. Consequently, the 24-hour marinated products required the highest puncture force, while 6-hour marinated biltong products required the least puncture force, within each drying system.

Table 4.5 The peak puncture force required to pierce through dry biltong samples of various thickness and marinating duration, that were dried under a convective air dryer, high wavelength (HWL) and low wavelength (LWL) infrared heaters

| Drying system | Pre-treatments | | Mean maximum puncture force (N) | Standard deviation (SD) |
|---|---|---|---|---|
| | Marinating duration (hours) | Thickness (mm) | | |
| Convective air dryer | 6 | 5 | $35.07^{k}$ | 1.5556 |
| | | 10 | $40.27^{j}$ | 1.9598 |
| | | 15 | $55.73^{h}$ | 1.9715 |
| | 12 | 5 | $60.57^{g}$ | 2.8501 |
| | | 10 | $77.63^{d}$ | 1.9397 |
| | | 15 | $92.20^{b}$ | 1.3839 |
| | 24 | 5 | $67.83^{e}$ | 1.4581 |
| | | 10 | $81.63^{cd}$ | 2.9501 |
| | | 15 | $131.33^{a}$ | 1.5258 |
| HWL IR heater | 6 | 5 | $39.36^{j}$ | 2.0305 |
| | | 10 | $46.37^{i}$ | 2.0984 |
| | | 15 | $62.47^{fg}$ | 1.8319 |
| | 12 | 5 | $39.63^{j}$ | 2.8790 |
| | | 10 | $53.07^{h}$ | 1.1820 |
| | | 15 | $65.55^{ef}$ | 2.1213 |
| | 24 | 5 | $44.73^{i}$ | 1.7711 |
| | | 10 | $61.57^{g}$ | 1.2910 |
| | | 15 | $83.73^{c}$ | 2.3055 |
| LWL IR heater | 6 | 5 | $12.27^{o}$ | 1.1214 |
| | | 10 | $15.17^{no}$ | 2.7815 |
| | | 15 | $19.45^{m}$ | 1.1830 |
| | 12 | 5 | $13.63^{no}$ | 2.4509 |
| | | 10 | $21.06^{m}$ | 0.9023 |
| | | 15 | $27.30^{l}$ | 1.6000 |
| | 24 | 5 | $18.07^{mn}$ | 2.3841 |
| | | 10 | $25.96^{l}$ | 1.6025 |
| | | 15 | $30.56^{l}$ | 2.0406 |

Means with different letters indicate a significant difference ($p \leq 0.05$).

There was a general decrease in the required peak puncture force in the order, LWL infrared dried biltong <HWL infrared dried biltong<convective air dried biltong. The high temperatures experienced during drying of biltong under the infrared drying systems may have caused cross linking reactions and interaction of proteins as a result of rapid rates of moisture loss (Thiagarajan, 2008). This may be responsible for the increasing tenderness as the drying temperature increased, as was the case for samples that were dried using the infrared heaters, when compared to the convective air drying system. The peak puncture force for samples dried under the HWL infrared heater were higher than those observed for samples that were dried under the LWL infrared heater. This difference may be attributed to the difference in product temperature under the two drying systems attributable to the differences in their peak emission wavelengths, as all the other experimental conditions were the same for the infrared heaters. The sample pre-treatment conditions were also the same for all the drying systems.

A three-factor ANOVA carried out on the data, showed significant ($p \leq 0.05$) differences between the mean peak puncture forces for the different drying systems. LSD tests showed significant difference in the mean peak puncture force between all the drying systems. There were also significant ($p \leq 0.05$) differences between the mean peak puncture forces for the different marinating durations. There were significant differences between the peak puncture forces for the 12- and 24-hour marinated samples. There were, however, no significant differences in the puncture force values between 6-hour marinated samples and the 12-hour marinated samples, as well as between the 6-hour marinated samples and 24-hour marinated samples.

There were also significant ($p \leq 0.05$) differences in the peak puncture force values between samples of different thickness. There were significant differences in the puncture force means between 5 and 15 mm thick samples. There were, however, no significant differences in the puncture force means between 10 and 15 mm thick samples as well as 5 and 10 mm thick samples. The interaction between the drying system and the product thickness or the marinating duration, as well as between the product thickness and the marinating duration was not statistically significant ($p \geq 0.05$) for the sample peak puncture force values. The three-way interaction between the drying system, product thickness and the marinating duration was also statistically not significant ($p \geq 0.05$).

The average peak puncture force values for the convective air dried samples was 22.7% and 70.5% higher than those of the HWL infrared heater and LWL infrared heater, respectively. Similarly, the average peak puncture force for the 24-hour marinated samples was 16.9% and 40.4% higher than those marinated for 12 hours and 6 hours, respectively. In addition, the average peak puncture force for the 15 mm thick samples was 24.6% and 41.7% higher than those of thicknesses of 10 and 5 mm, respectively. Lower peak puncture force values imply better texture and improved palatability.

**Texture profile analysis**

Texture profile analysis (TPA) mimics (imitative test) the sensation perceived in a human mouth when a food sample is chewed, usually in two successive bites. Details of the test are as discussed in Sections 2.5.2 and 3.4.2.

Table 4.6 presents the results of TPA tests where the hardness values of samples that were dried after different pre-treatment conditions using the three drying systems ranged from 4.71 kgf to 33.12 kgf. It is evident that the hardness values generally increased with increasing marinating time for all product thicknesses (Table 4.6). This behaviour is consistent with observations made by Thiagarajan (2008). Increasing marinating time increases salt and spice uptake in the marinated samples. Increased salt content in dried meats is known to increase product hardness due to increased protein binding and cross-linking of myofibrils during drying (Thiagarajan *et al.*, 2006; Thiagarajan, 2008).

The cohesiveness for the prepared biltong, using diverse conditions before drying, ranged from 0.28 to 0.62. Cohesiveness decreased with increasing marinating time for all slice thickness within the different drying systems. This trend is also consistent with that observed by Thiagarajan (2008), where the combined convective-microwave drying of jerky was investigated, and hardness values ranging from 0.38 to 0.76 reported.

Gumminess of the samples ranged from 1.41 kgf to 12.92 kgf. Generally, the product gumminess increased with increasing marinating time. Gumminess values ranging from 1.2273 to 4.1580 kgf as reported by Thiagarajan (2008), were lower than those presented in the present study. However, the cohesiveness values ranging from 0.38 to 0.76 reported by Thiagarajan (2008) were not far removed from those reported in this study. The product thickness and its effect on the textural characteristics of Jerky as evidenced through TPA, was however, not investigated. The hardness values of biltong in the present study are not far

removed from those reported by Morales et al., (2007) in their study where TPA of dry cured ham under different pre-treatment and drying conditions was investigated.

The hardness and gumminess of biltong slices dried under different conditions increased with increasing thickness, regardless of the dyer used and the marinating duration the samples were subjected to. However, the product cohesiveness decreased with increasing product thickness regardless of the samples' marinating duration or the drying system used to dry biltong. Product hardness is expected to increase with increasing product thickness, due to the increase in myofibril and muscle fibres.

Table 4.6 The texture profile analysis (TPA) values for samples of various thickness and marinating duration that were under a convective air, high wavelength (HWL) and low wavelength (LWL) infrared heaters

| Drying system | Sample pre-treatments | | TPA values | | |
|---|---|---|---|---|---|
| | Marinating time (hours) | Thickness (mm) | Hardness (kgF) | Cohesiveness | Gumminess (kgF) |
| Convective air dryer | 6 | 5 | 5.35± 1.85$^{ml}$ | 0.62±0.054$^{b}$ | 3.33±0.27$^{k}$ |
| | | 10 | 8.83± 1.52$^{k}$ | 0.49±0.021$^{d}$ | 4.12±0.11$^{j}$ |
| | | 15 | 20.90±1.47$^{de}$ | 0.47±0.040$^{d}$ | 10.16±0.59$^{de}$ |
| | 12 | 5 | 9.82±1.73$^{j}$ | 0.46±0.039$^{de}$ | 4.55±0.29$^{i}$ |
| | | 10 | 11.15±1.00$^{ij}$ | 0.43±0.042$^{e}$ | 4.71±0.43$^{i}$ |
| | | 15 | 23.64±1.67$^{d}$ | 0.42±0.054$^{e}$ | 10.18±1.10$^{de}$ |
| | 24 | 5 | 17.03±1.45$^{fg}$ | 0.44±0.010$^{e}$ | 7.49±0.045$^{g}$ |
| | | 10 | 21.99±1.52$^{dc}$ | 0.39±0.043$^{e}$ | 7.93±0.664$^{fgh}$ |
| | | 15 | 33.12±1.25$^{a}$ | 0.36±0.087$^{efg}$ | 12.92±0.021$^{c}$ |
| HWL Infrared heater | 6 | 5 | 10.04±1.23$^{j}$ | 0.61±0.029$^{bc}$ | 6.17±0.65$^{h}$ |
| | | 10 | 13.42±1.22$^{h}$ | 0.50±0.042$^{d}$ | 6.82±0.51$^{h}$ |
| | | 15 | 27.00±0.91$^{c}$ | 0.47±0.094$^{d}$ | 12.69±0.92$^{c}$ |
| | 12 | 5 | 13.11±1.28$^{hi}$ | 0.65±0.068$^{a}$ | 8.47±0.22$^{f}$ |
| | | 10 | 18.78±1.65$^{fg}$ | 0.51±0.071$^{d}$ | 9.66±0.46$^{d}$ |
| | | 15 | 28.94±1.32$^{bc}$ | 0.49±0.069$^{d}$ | 14.45±0.23$^{b}$ |
| | 24 | 5 | 18.95±1.60$^{f}$ | 0.62±0.078$^{b}$ | 10.71±0.47$^{de}$ |
| | | 10 | 19.63±1.93$^{ef}$ | 0.55±0.043$^{d}$ | 10.73±0.84$^{de}$ |
| | | 15 | 31.39±1.57$^{ab}$ | 0.54±0.076$^{d}$ | 16.99±0.35$^{a}$ |
| LWL Infrared heater | 6 | 5 | 4.71±1.11$^{ml}$ | 0.45±0.015$^{e}$ | 1.41±0.16$^{m}$ |
| | | 10 | 5.40±1.38$^{ml}$ | 0.43±0.044$^{e}$ | 2.32±0.17$^{j}$ |
| | | 15 | 8.72±0.98$^{k}$ | 0.31±0.048$^{ef}$ | 3.89±0.29$^{n}$ |
| | 12 | 5 | 4.86±0.62$^{ml}$ | 0.51±0.035$^{d}$ | 2.48±0.20$^{l}$ |
| | | 10 | 9.31±1.02$^{jk}$ | 0.36±0.016$^{e}$ | 3.31±0.10$^{j}$ |
| | | 15 | 10.81±1.29$^{ij}$ | 0.30±0.086$^{ef}$ | 4.25±0.25$^{ij}$ |
| | 24 | 5 | 6.58±1.98$^{l}$ | 0.45±0.063$^{de}$ | 2.95±0.62$^{kl}$ |
| | | 10 | 11.56±1.66$^{hij}$ | 0.34±0.058$^{efg}$ | 3.93±0.96$^{ijk}$ |
| | | 15 | 15.78±1.49$^{g}$ | 0.28±0.046$^{g}$ | 4.42±0.15$^{i}$ |

Means in the same column with different letters indicate a significant difference ($p<0.05$).

The TPA values were generally higher for the samples that were dried under the convective air dryer compared to those of samples dried under the two infrared heaters. The TPA values for biltong slices dried under the LWL infrared heater were the lowest of the three drying systems tested indicating increased tenderness with increase in drying temperature (Martinez *et al.*, 2004). The high drying temperatures and drying rate experienced by samples dried under the two infrared heaters may have brought about proteolytic reactions that caused structural weakening and loosening of myofibrils (Tornberg, 1996).

A three-factor ANOVA of the hardness values of biltong, showed significant ($p \leq 0.05$) difference between the hardness values for samples dried under different drying systems. LSD tests showed significant difference in hardness values of biltong slices dried under the convective air dryer and LWL infrared heater as well as between those dried under the LWL and HWL infrared heaters. The differences in the hardness values between samples dried under the convective air dryer and HWL infrared heater was not significant. There were also significant ($p \leq 0.05$) differences in the hardness values for dry biltong products of different thicknesses. There were significant differences in hardness values between 5 and 15 mm thick slices, as well as between 10 and 15 mm thick slices. The difference in hardness values between 10 and 5 mm thick biltong slices was not significant.

The degree of marination did not significantly ($p \geq 0.05$) affect the hardness of the samples. Similarly, the marinating duration did not appear to significantly ($p \geq 0.05$) affect the cohesiveness of the samples. There were however, significant ($p \leq 0.05$) differences in the cohesiveness between samples dried under different drying systems. LSD tests showed significant differences in cohesiveness between samples dried under all the drying systems, with biltong dried under the convective air drying system recording higher cohesiveness values compared to those dried under the HWL and LWL infrared heaters.

There were also significant ($p \leq 0.05$) differences in cohesiveness between samples of different thickness. The cohesiveness between samples of 5 and 10 mm thick samples as well as 5 and 15 mm were significantly different. The differences in cohesiveness values between samples of 10 and 15 mm thickness was, however, not significant. In addition, the 5 mm thick samples under different drying systems and marinated to different durations recorded the highest cohesiveness. ANOVA results for gumminess followed the same trend as the ANOVA results for cohesiveness. The interaction between the drying system and the product thickness or the marinating duration, as well as between the product thickness and the

marinating duration was not statistically significant ($p \geq 0.05$) for the sample hardness, cohesiveness and gumminess. In addition, the three-way interaction between the drying system, product thickness and the marinating duration was also statistically not significant ($p \geq 0.05$).

The mean hardness for samples dried in HWL infrared heater was 16.3% and 57.1% higher than the mean hardness values for samples that were dried under the convective air dryer and LWL infrared heater, respectively. Similarly, the mean hardness for the 15 mm thick biltong slices was 40% and 54.8% higher than the mean hardness values for 10 and 5 mm thick biltong slices, respectively. Other TPA parameters (chewiness, springiness and resilience) followed the trends observed for the hardness, cohesiveness and gaminess and the data for these parameters is given in Appendix K. A typical TPA curve of biltong products is shown in Appendix M.

### 4.4.3 Shrinkage

Biltong slices that were dried under different drying systems and pre-treatment conditions, shrunk to varying levels. Table 4.7 presents the shrinkage coefficients of biltong products that were dried under the three drying systems after different pre-treatments.

Table 4.7 Shrinkage coefficients for samples of various thickness and marinating duration, that were dried under a convective dryer, high wavelength (HWL) and low wavelength (LWL) infrared heaters

| Pre-treatments | | Shrinkage coefficient (%) | | |
|---|---|---|---|---|
| Marinating duration (hours) | Product thickness (mm) | Convective air dryer | HWL infrared heater | LWL infrared heater |
| 6 | 5 | $62.5 \pm 3.13^{d}$ | $70.09 \pm 1.85^{bc}$ | $64.02 \pm 0.97^{a}$ |
| | 10 | $55.3 \pm 2.25^{f}$ | $63.90 \pm 2.20^{de}$ | $57.37 \pm 1.86^{de}$ |
| | 15 | $52.9 \pm 1.09^{g}$ | $61.38 \pm 1.22^{e}$ | $54.71 \pm 1.37^{e}$ |
| 12 | 5 | $64.58 \pm 1.32^{c}$ | $73.81 \pm 1.68^{a}$ | $64.69 \pm 0.98^{a}$ |
| | 10 | $59.26 \pm 1.42^{e}$ | $67.88 \pm 2.29^{cd}$ | $60.22 \pm 0.92^{c}$ |
| | 15 | $54.55 \pm 2.35^{f}$ | $61.96 \pm 1.17^{de}$ | $58.82 \pm 1.70^{cd}$ |
| 24 | 5 | $80.49 \pm 2.52^{a}$ | $74.09 \pm 1.29^{a}$ | $65.02 \pm 2.71^{ab}$ |
| | 10 | $73.77 \pm 1.82^{b}$ | $71.21 \pm 1.71^{ab}$ | $61.51 \pm 1.40^{b}$ |
| | 15 | $64.47 \pm 0.95^{c}$ | $65.3 \pm 2.60^{d}$ | $59.48 \pm 1.22^{cd}$ |

Means in the same row with different letters indicate a significant difference ($p<0.05$)

The shrinkage coefficient of biltong slices in this study ranged from 52.9% to 80.49%. Thiagarajan (2008) in the study where jerky was dried under combined convective-microwave drying reported shrinkage coefficients that ranged from 32.14% to 60.44%. These values are lower than those observed in the present study. Differences in these values may be attributed to differences in the drying temperature and drying times. Long drying times, as was the case in in the present study, as well as slow drying rates and low drying temperatures give products more time to shrink (Maskan, 2001a; Nathakaranakule *et al.*, 2007)

It can be clearly observed in Table 4.7 that the shrinkage of biltong products under a specific drying system generally decreased with increasing product thickness when the marinating duration is held constant. It can be also seen that shrinkage increased with increasing marinating time. Increasing marinating time implies increased salt and spice uptake and therefore, products with higher salt content shrunk more. This observation is consistent with that reported by Thiagarajan *et al.* (2006)

Three-factor ANOVA of the data showed that the drying system, product thickness and marinating time had a significant ($p \leq 0.05$) effect on biltong's shrinkage coefficient. There were significant differences in the shrinkage coefficient values between HWL infrared dried and LWL infrared dried samples. The shrinkage coefficient values between samples dried under the convective air dryer and HWL infrared heater, as well as those dried under the convective air dryer and LWL infrared heater were not significantly different. There were also significant differences in the shrinkage coefficient values between samples that were marinated for 6 and 24 hours as well as between those samples that were marinated for 12 and 24 hours. The difference in the shrinkage coefficient values between samples that were marinated for 6 and 12 hours was not significant. Samples of 5 and 10 mm thickness had significant differences in their shrinkage coefficient values. This was also the case between samples of 5 and 15 mm thickness. However, the shrinkage coefficient between 10 and 15 mm thick samples was not significantly different. The interaction between the drying system and the product thickness or the marinating duration, as well as between the product thickness and the marinating duration was not statistically significant ($p \geq 0.05$) for the shrinkage coefficient. The three-way interaction between the drying system, product thickness and the marinating duration was also statistically not significant ($p \geq 0.05$).

Generally, HWL infrared dried samples shrunk more than convective air dried samples and the LWL infrared dried Samples evidenced by a higher mean shrinkage coefficient of 67.73%

compared to a mean shrinkage coefficient of 63.09% and 60.64% for Samples dried under the convective air dryer and LWL infrared heater, respectively. In addition, 5 mm thick biltong slices shrunk more than the 10 and 15 mm thick samples. Similarly, samples that were marinated for 24 hours shrunk more than those that were marinated for 6 and 12 hours.

Excessive shrinkage has a direct relationship with structural collapse in the food matrix, an undesirable phenomenon that should be avoided in food processing as it negatively affects the food's texture (Yan *et al.*, 2008). Excessive shrinkage also has a negative impact on product packaging (Yadollahinia and Jahangiri, 2009). From a quality stand point, and using shrinkage as a quality indicator, samples dried under the convective air dryer compared well to those of the two infrared drying systems. However, 6-hour marinated and 15 mm thick Samples gave lower shrinkage values indicating better quality.

### 4.4.4 Rehydration

Ready-to-eat (RTE) meat products are commonly not evaluated using rehydration as a quality parameter. It is important to note, however, that rehydration rates have a direct bearing on the palatability of these products since they must be masticated and mixed with saliva to soften them before swallowing.

The rehydration characteristic curves for samples of different thickness marinated for 6 hours and dried under the convective air dryer are shown in Figure 4.23. These curves are typical of samples of other marinating durations that were dried under the same conditions (see appendix I). It can be seen that for the samples that were dried under the convective air dryer, 5 mm thick biltong slices rehydrated better than the 10 and 15 mm thick slices while the 15 mm thick slices had the slowest rehydration rates for all thicknesses. The rehydration rises from zero to reach 8.47% after two minutes for 5 mm thick slices, and gradually increases with increasing rehydration time to reach 11.84% after the 10 minutes (Figure 4.23). It can also be observed in that samples of 10 and 15 mm thickness followed a similar trend, although their rehydration rates were lower than that of 5 mm thick slices, with the 15 mm thick slices having the slowest rehydration rates. Samples that had been marinated for different durations showed comparable rehydration characteristics (Appendix I).

Figure 4.24 shows rehydration characteristics of 5 mm thick biltong slices that were marinated for different durations then, dried under the convective air dryer. It can be observed that the 5 mm thick, 24-hour marinated samples' rehydration rises rapidly from zero

to reach 7.29% in a minute. Thereafter, rehydration gradually increased with increasing rehydration time to reach 12.16% in 10 minutes (Figure 4.24). It can also be deduced that the 5 mm thick, 6- and 12- hour marinated samples followed a similar trend, although their rehydration rates were lower than those of 5 mm thick, 12- and 24-hour marinated slices, with the 5 mm thick, 12-hour marinated slices having the slowest rehydration rates. Sample thickness had a more pronounced effect on rehydration than the marinating duration (Figures 4.23 and 4.24)

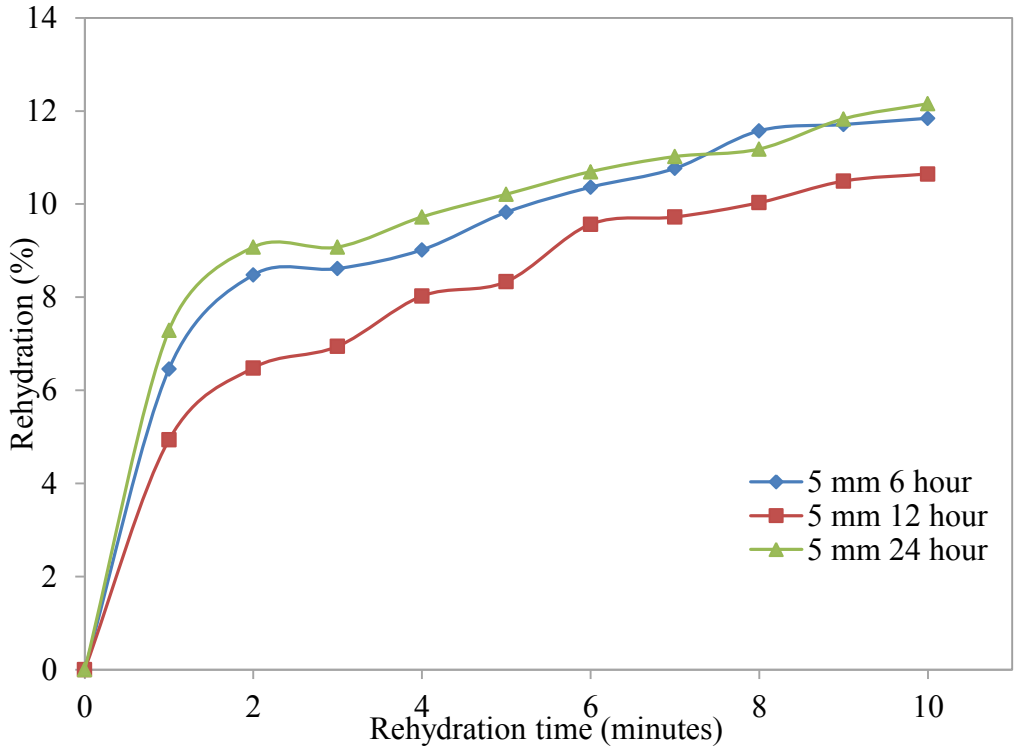


Figure 4.23 Changes in rehydration with time, when the marinating duration is varied, for 5 mm thick, convective air dried samples

Figure 4.25 presents the rehydration characteristics of samples of different thicknesses previously marinated for six hours then dried under the HWL infrared heater. These curves are typical shape of rehydration curves of 12- and 24-hour marinated that were dried under the same conditions using the HWL infrared heater (see Appendix I). It can be observed in (see Figure 4.25) that the rehydration of 5 mm thick slices rises from zero to 5.36% within a minute, and gradually increases with increasing rehydration time. After 10 minutes of rehydration, it had risen to 12.59%. It is also that samples of 10 and 15 mm thickness followed a similar trend, although their rehydration rates were lower than that of 5 mm thick slices, with the 15 mm thick slices having the slowest rehydration rates for all thicknesses

regardless of the marinating duration for samples that were dried under the HWL infrared heater. Similarly, samples that had been marinated for different durations and dried under the HWL infrared heater showed similar rehydration characteristics to those that were dried under the convective air dryer.

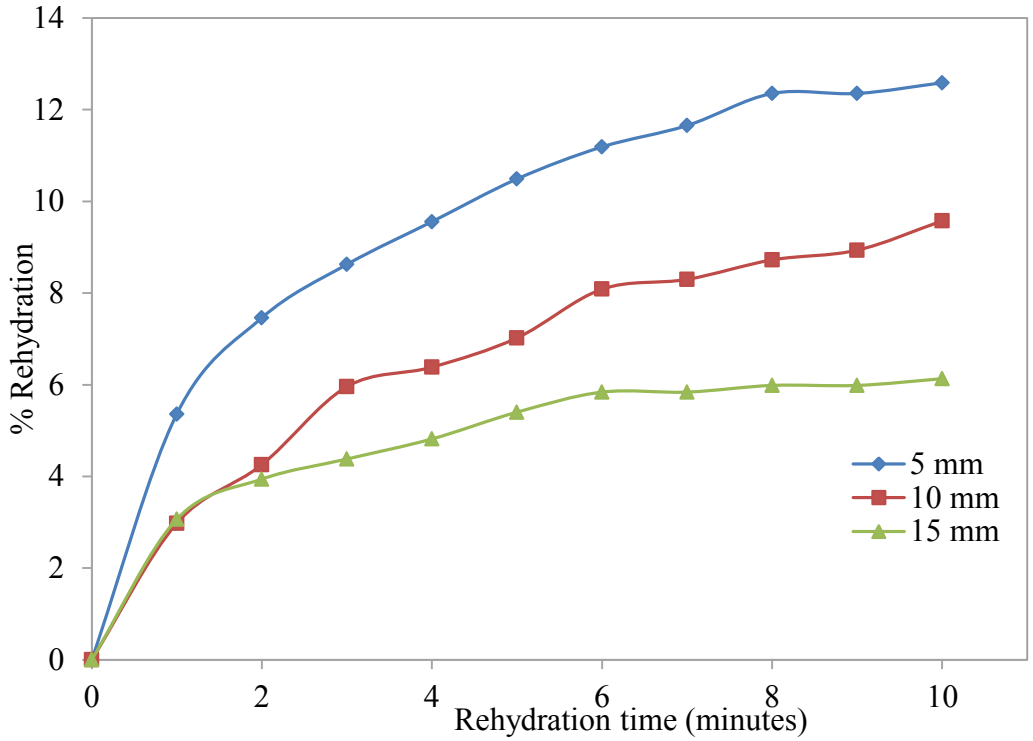


Figure 4.24 Changes in rehydration as a function of time, when the slice thickness is varied, for the 6-hour marinated, high wavelength (HWL) infrared dried samples

Figure 4.26 shows the rehydration characteristics of 5 mm thick samples that were marinated for different durations, then dried under the HWL infrared heater. It can be observed form that the rehydration for the 5 mm, 6-hour marinated biltong slices rises from zero to 5.36% after a minute, and gradually increases with increasing rehydration time. After 10 minutes, its rehydration was 12.59%.

It can be also be deduced that the 5 mm thick,12- and 24-hour marinated samples followed a similar trend, although their rehydration rates were lower than that of the 6-hour marinated slices, with the 5 mm 24-hour marinated slices having the slowest rehydration rates for all marinating durations (Figure 4.26). The product thickness had a more pronounced effect on rehydration than marinating duration (Figures 4.25 and 4.26).

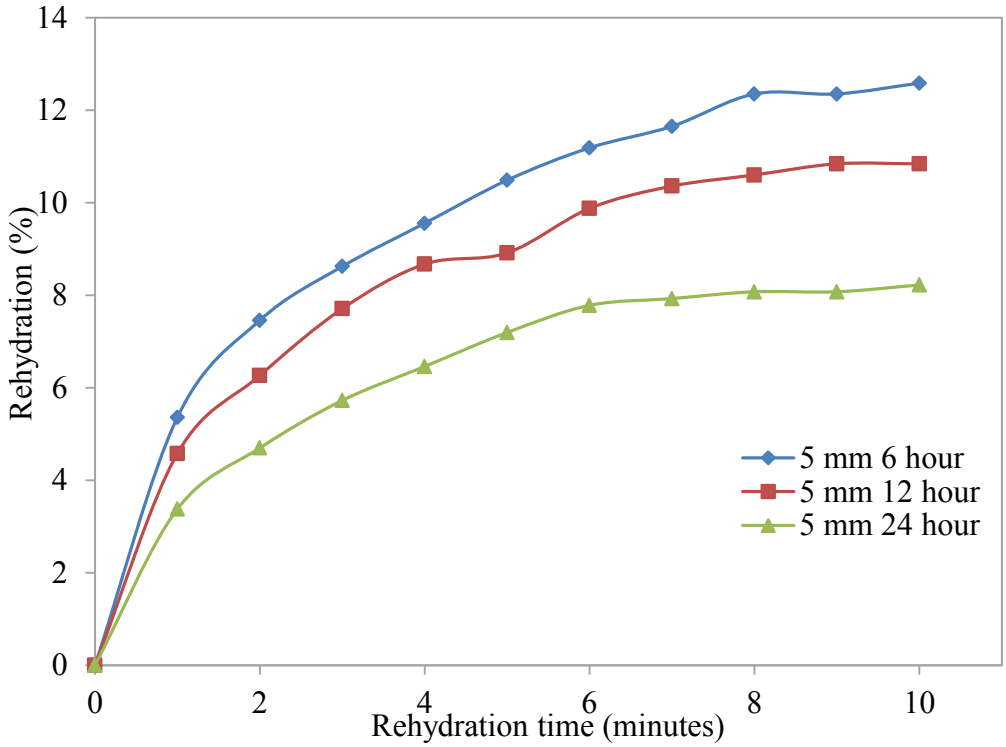


Figure 4.25 Changes in rehydration as a function of time, when the marinating duration is varied, for the 5 mm thick, high wavelength (HWL) infrared dried samples

Figure 4.27 presents the rehydration behaviour for samples of various thicknesses that were marinated for 24 hours, then dried under the LWL infrared heater. These rehydration curves are the typical shape of rehydration curves of samples of various thickness that were dried under the same conditions after marinating for 6 and 12 hours (see Appendix I). It can be deduced that the 5 mm thick slices rehydrated from zero to 3.37% after a minute, and gradually increased with increasing rehydration time. After 10 minutes, its rehydration was 9.44%.

It can also be observed that samples of 10 and 15 mm thickness followed a similar trend although their rehydration rates were lower than that of 5 mm thick slices with the 15 mm thick slices having the slowest rehydration rates for all thicknesses, for samples that were dried under the LWL infrared heater (Figure 4.27). Samples that were marinated for different durations showed similar behaviour to the rehydration characteristics of samples that were marinated for 24 hours, depicted in Figure 4.27 (see Appendix I).

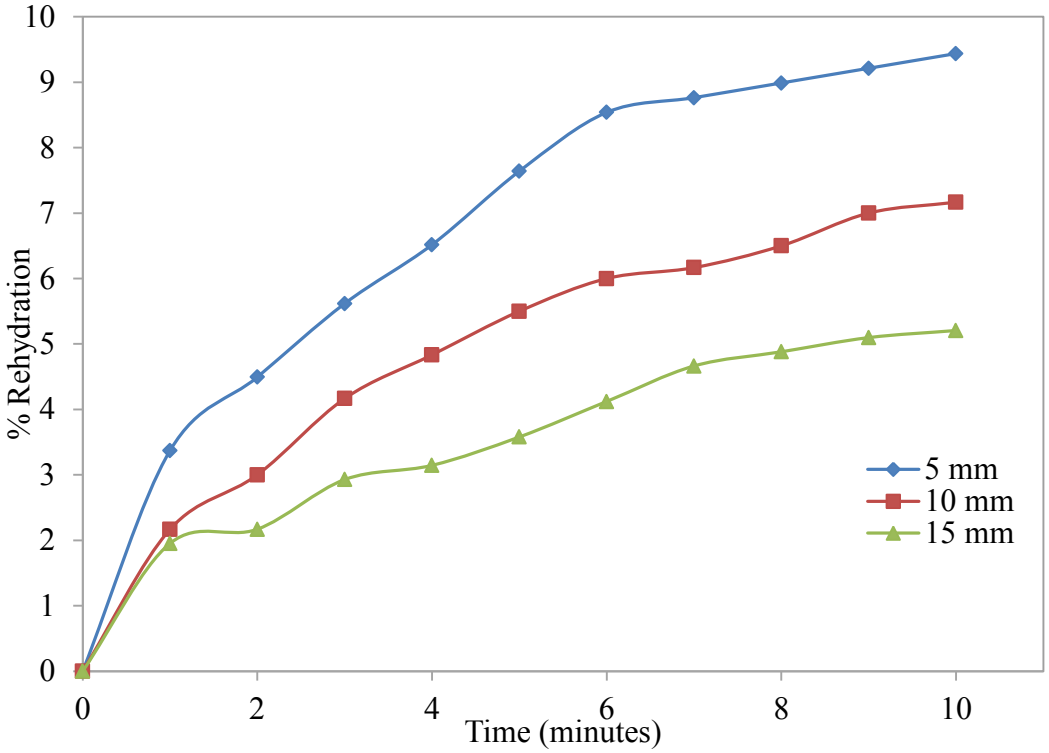


Figure 4.26 Changes in rehydration as a function of time, when the slice thickness is varied, for the 24-hour marinated, low wavelength (LWL) infrared dried samples

Figure 4.28 presents rehydration characteristics of 10 mm thick biltong slices that were marinated for 6, 12 and 24 hours then dried under the LWL infrared heater. It can be observed that the 10 mm, 6-hour marinated biltong slices rehydration rose from zero and reached 4.25% in a minute, and then gradually increased with increasing rehydration time (Figure 4.28). After 10 minutes, its rehydration was 12.57%. It can be also be clearly seen that the 10 mm thick samples that were marinated for 12 and 24 hours followed a similar trend, although their rehydration rates were generally lower than those marinated for 6 hours, with the 24-hour marinated slices having the slowest rehydration rates for all marinating durations. It can also be observed from the rehydration curves in Figure 4.27 and Figure 4.28 that the differences in rehydration rates due to product thicknesses appear to be comparable to differences in rehydration due different marinating durations. It can be conclude that the 6-hour marinated slices (see Figure 4.28), had better rehydration characteristics compared to those of 12- and 24-hour marinated biltong slices.

Samples dried under the three drying systems showed that the HWL infrared heater had better rehydration characteristics than those dried under the LWL heater and the convective air dryer. In addition, 5 mm thick biltong slices had higher rehydration rates than 10 and 15 mm

thick samples. However, marinating duration had varied effects on biltong products dried under each of the three drying systems assayed. Samples that were marinated for 24 hours, had higher rehydration rates than those marinated for 6 and 12 hours for biltong slices that were dried under convective air drying system. On the other hand, samples marinated for 6 hours had higher rehydration rates compared to those that were marinated for 12 and 24 hours for biltong slices that were dried under the HWL and LWL infrared heaters.

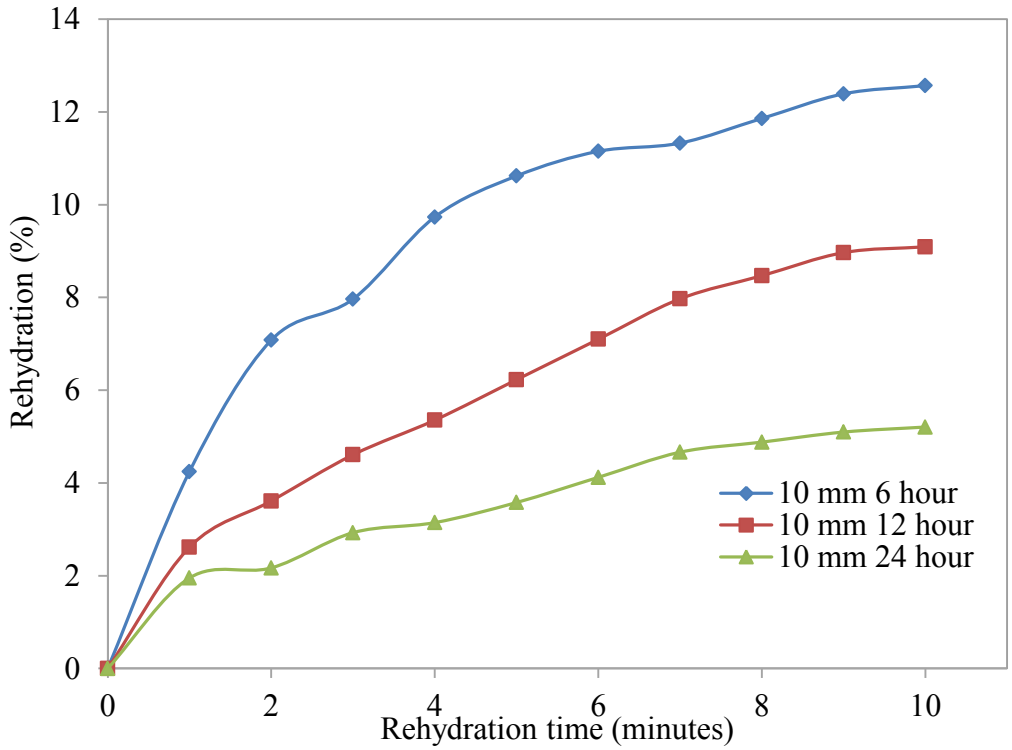


Figure 4.27 Changes in rehydration as a function of time, when the marinating duration is varied, for the 10 mm thick, low wavelength (LWL) infrared dried samples

It was observed that when samples were rehydrated for durations longer than 10 minutes, there was an increase in their rehydration. It is expected that, with an increase in rehydration time beyond 10 minutes, there will be a gradual increase in rehydration to a point where rehydration will no longer increase with increasing rehydration time.

A three-way ANOVA was carried out on the mean rehydration values for the samples in order to investigate the effects of product thickness, marinating time and the drying system on the rehydration characteristics of biltong. Both the drying system used to dry the samples and the marinating time had no significant ($p \geq 0.05$) effect on the average rehydration rates of biltong slices. There was however significant ($p \leq 0.05$) differences between the average rehydration rates for dry samples of different thicknesses. The average rehydration rates

between samples of all thicknesses were significantly different. The interaction between the drying system and the product thickness or the marinating duration, as well as between the product thickness and the marinating duration was not statistically significant ($p \geq 0.05$) for product rehydration. The three-way interaction between the drying system, product thickness and the marinating duration was also statistically not significant ($p \geq 0.05$).

In summary, the sample thicknesses had a significant effect on the rehydration rates of biltong while the drying system used as well as different the marinating durations assayed, gave comparable rehydration behaviour of biltong products. The rehydration values in this study were, however, low compared to those reported in studies by Nathakaranakule *et al.* (2007) that ranged from 57.17% to 86.66%. Differences in rehydration rates between their study and the present study may be attributed to differences in the drying method used and the inherent biological constitution of the products under investigation. In their study, they rehydrated chicken meat that was dried using superheated steam and heat pump-assisted superheated steam, and this implies a product of lower fibre density compared to that of beef, and a drying system that operated at higher temperatures (above $100^{o}$C) compared to those of the present study.

### 4.4.5 Microbiological safety

#### Microbial load

Dried ready-to-eat (RTE) meat products should primarily have acceptable levels of microbial reductions for their shelf stability and safe consumption. Tables 4.8 and 4.9 presents the MPN counts for fresh beef and biltong slices for presumptive and confirmed counts, respectively. It is evident that the fresh beef slices had high microbial loads with most the probable number (MPN) of the fresh beef slices marginally exceeding the acceptability threshold, according to the South African Department of Agriculture, Forestry and Fisheries, Australian Food Safety Standards and the EU food safety standards. These standards require fresh beef to have bacterial counts of less than 5 logs for it to be acceptable (Commission of European Communities, 2005)

Table 4.8 Presumptive most probable number (MPN) counts of fresh beef and biltong samples that were dried under the convective air dryer, high wavelength (HWL) and low wavelength infrared heaters

| Sample | MPN/g | Log MPN | SE Log MPN |
|---|---|---|---|
| Fresh beef | 440,802 | 5.644 | 0.2563 |
| Convective dried biltong | 7,029 | 3.847 | 0.2517 |
| HWL infrared dried biltong | 4,077 | 3.610 | 0.2460 |
| LWL infrared dried biltong | 2,952 | 3.470 | 0.2433 |

*Turbidity observations in incubated tubes made after 24 hours – presumptive

Table 4.9 Conclusive most probable number (MPN) counts of fresh beef and biltong samples that were dried under the convective air dryer, high wavelength (HWL) and low wavelength (LWL) infrared heaters

| Sample | MPN/g | Log MPN | SE Log MPN |
|---|---|---|---|
| Fresh beef | 1,163,403 | 6.066 | 0.2325 |
| Convective dried biltong | 70,353 | 4.847 | 0.2517 |
| HWL infrared dried biltong | 24,300 | 4.386 | 0.1898 |
| LWL infrared dried biltong | 7,020 | 3.846 | 0.2410 |

**Turbidity observations in incubated tubes made after 48 hours – conclusive

MPN counts in food samples analyse the total viable count (TVC) of bacterial cells that are able to grow and multiply in the food. MPN counts in this study showed a general reduction in microbial counts as the processing temperature increased. It can be concluded that samples that were dried under the convective air dryer and the HWL infrared heater had high proportions of slow-growing coliforms due to over five-fold increase in the total bacterial cells (MPN/g) between the presumptive and confirmed counts. Samples dried under the LWL infrared heater had the highest microbial log reduction of 2.2.

Nortjé *et al.* (2005) and Naidoo (2010) showed that commercial biltong products have TVC counts of between 6-7 logs/g. Therefore, MPN counts in the present study were 1.153 to 3.315 logs lower than those reported in their studies indicating good microbial levels, especially for samples that were dried under the LWL infrared heater. Raji (2006) also investigated the microbial safety of dried, sliced beef (kilishi) sold in the Ilorin metropolis and reported total microbial counts ranging from log 4.38 to 4.54 CFU/g.

In another study by Naidoo and Lindsay (2010) where the microbial safety of biltong from three commercial retail outlets in Johannesburg was investigated, total counts ranging from 6-7 logs/g were reported. The overall quality of biltong processed under both the convective

and infrared conditions was therefore remarkably good in terms microbial contamination when compared to that of commercially-produced biltong products.

**Identification and isolation of *E. coli***

*E. coli* is an indicator organism in food products that can be used to assess the sanitary and overall microbial safety levels in their production (Gill *et al.*, 1996; Cassin *et al.*, 1998; Reij and den Aantrekker, 2004; Naidoo and Lindsay, 2010). Table 4.10 presents the results of Eosin methylene blue (EMB) culture plates that were used to detect the presence of *E. coli* in the fresh beef slices and dry samples. EMB plates of fresh beef samples did not show the presence of *E. coli*. The Australian standards would, therefore, categorize the freshly sliced beef as of excellent microbial quality due to the undetectable levels of *E. coli* in these samples.

Table 4.10 Eosin methylene blue (EMB) culture plate results for fresh beef and biltong samples that were dried under the convective air dryer, high wavelength (HWL) and low wavelength (LWL) infrared heaters

| Sample | Presence of *E-coli* in $10^{-1}$ ST1 broth tubes | | | | | *E-coli* plate count (Log CFU/g) |
|---|---|---|---|---|---|---|
| | Tube 1 | Tube 2 | Tube 3 | Tube 4 | Tube 5 | |
| Fresh beef | – | – | – | – | – | Not detected |
| Convective dried biltong | + | + | + | + | + | 4.045 |
| HWL infrared dried biltong | + | + | + | – | + | 1.893 |
| LWL infrared dried biltong | – | – | – | – | – | Not detected |

The convective air dried samples had high numbers of *E. coli* colonies indicated by the presence of nucleated and dark colonies with a metallic green sheen. The colonies (plate count) in this case were log 4.045 CFU/g .This number was well in excess of $10^2$ CFU/g acceptability threshold for *E. coli* in RTE meat products (Commission of European Communities, 2005). There were *E. coli* colonies in four of the five EMB plates for samples dried under the HWL infrared heater. The number of *E. coli* colonies in the plates was log 1.893 CFU/g and therefore, passed the acceptability threshold. No *E. coli* colonies or any other colonies were detected in EMB plates for biltong products that were dried under the LWL infrared heater.

The microbial hurdles used in the handling of fresh beef as well as in the process of making biltong effectively suppressed the microbial populations in the meat. RTE meats should be

processed to temperatures that exceed 70$^{o}$C as this is known to be the thermal lethality threshold that effectively sterilizes *E. coli* (Seyer *et al.*, 2003; Dierschke *et al.*, 2010). From Figure 4.2 and Figure 4.3, it can be observed that the HWL infrared heater did not exceed the lethality temperature of 70$^{o}$C known to eliminate *E. coli*. Similarly, samples that were dried in the convective air system did not reach the lethality temperature as they dried at an air temperature of about 25$^{o}$C (the convective air dryer set-point temperature)

The product temperatures in the case of the LWL infrared heater exceeded 70$^{o}$C as can be seen in Figure 4.4 and Figure 4.5 and this explains why the LWL infrared heater effectively sterilized *E. coli* as the core temperature of samples dried in this dryer exceeded the lethality temperature. This therefore, implies that LWL infrared dried samples had excellent microbial quality that guaranteed microbiological safety to consumers and better shelf-life of the dried products compared to samples dried under the other drying systems.

# 5. CONCLUSION AND RECOMMENDATIONS

## 5.1 Conclusions

This study was undertaken to establish the drying kinetics of biltong under two infrared heaters with different peak emission wavelengths, but set at the same infrared intensity. The quality characteristics and drying kinetics of samples dried under the infrared systems were compared to those of biltong dried under convective air drying, which mimics the conventional way of drying biltong that is also used by commercial producers of biltong. The implications of the product pre-treatment conditions and drying kinetics under the three drying systems on the product quality and its food safety have also been established.

The following conclusions can be made from the findings of this research:

a) The drying times for biltong dried under the convective air drying system were 84.6% and 95.6% longer than the drying times for samples dried under the HWL and LWL infrared heaters, respectively. Changing from one drying system to another resulted in a significant ($p \leq 0.05$) change in the drying time. Increasing the product thickness increased the drying times by 10 to 16% for all drying systems tested. Similarly, increasing the marinating duration increased the drying times by 55 to 76% for all drying systems except the LWL infrared heater.

b) The mean SEC of the LWL infrared heater was generally .higher than that of the HWL infrared heater. Generally, the energy consumption of the infrared drying systems in the present study was higher than those reported in other studies in the literature.

c) The product temperature of biltong products during drying generally reduced with increasing product thickness for the LWL infrared heater. The effect of varying product thickness on the product temperature in the case of the HWL infrared system was inconclusive.

d) Out of the five drying models tested, the ADM model best described the drying kinetics of sliced biltong under the LWL, HWL and the convective air drying systems compared to the other models.

e) The L* a* b* colour attributes decreased when fresh beef samples were marinated and decreased even further after drying. The average total colour difference ($\Delta E$) of LWL

infrared dried samples was 53% and 66% higher than that of the HWL infrared heater and the convective air dryer, respectively. The drying system used and the product thickness had a significant ($p \leq 0.05$) effect on the L* values of dry biltong slices while the a* values were significantly ($p \leq 0.05$) influenced by a change in product thickness. Product thickness and the drying system used significantly influenced the yellowness (b*) of dried biltong. All products from the drying systems were of acceptable quality in terms of colour with products produced using the infrared systems comparing well to those produced using the convective air dryer.

f) Samples that were dried under the LWL infrared heater recorded lower hardness and peak puncture force values compared to samples that were dried under the HWL infrared heater and the convective air drying system. Soft products are usually more acceptable.

g) HWL infrared dried samples recorded higher shrinkage coefficient values than those dried either under the LWL infrared heater or the convective air dryer. Increasing product thicknesses and reducing marinating durations had an effect of reducing the shrinkage coefficient, irrespective of the drying system used to dry the products.

h) HWL infrared dried products generally recorded higher rehydration rates than the convective air dried samples and the LWL infrared dried samples, with rehydration rates increasing with decreasing product thickness, regardless of the drying system used to dry the products or the marinating duration they were treated to. The effect of marination on rehydration was dependent on the drying systems.

## 5.2 Recommendations

The present study has also exposed the following areas of study that call for further research, as well as general recommendations necessary to improve the production processes of biltong. These include:

a) Sensory analysis should be carried out to establish how well the instrument TPA data correlate to the sensory analysis data from sensory panellists.

b) Further studies on energy consumption of the infrared heaters should be carried out under different energy intensities and loadings. Combined convective-infrared drying of biltong should also be investigated at different air velocities and pyschrometric properties of the heated air, in order to establish the configurations that would give the

highest energy efficiency.

c) Food safety standards that are specific to the production of biltong should be developed in collaboration with the relevant government agencies–such as the USDA'S food safety and inspection service (FSIS) standards for the production of jerky.

d) There is need for further investigation of the effects of other microbial hurdles on the microbiological safety of biltong.

e) Storage studies should be carried out to evaluate the conditions under which biltong has the best quality and extended shelf-life.

f) The effects of different packaging materials on the shelf-life and quality of biltong should be investigated.

g) The profound food safety issues associated with the production of biltong under the convective air drying system has been confirmed. Infrared drying provides a good alternative in tackling the food safety concerns associated with the conventional production of biltong, and assures microbiologically safe products. The study, therefore, recommends infrared drying to the biltong industry, because it produces biltong with acceptable food safety characteristics, as well as generally high quality products that are comparable to the conventional convective air dryers. In the same vein, stringent and enforced production protocols for the production of biltong should be developed by research institutions, in conjunction with the relevant ministries, and the same should be enforced as a national standard in South Africa. This will ensure that high quality biltong across the South African market is produced, as opposed to the current trend where every production entity has its own "standards".

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# 7. APPENDICES

## APPENDIX A

Table 7.1 A summary of 52 publications depicting the best drying model

| Number | Paper DOI | Number of models tested | Best model | Count |
|---|---|---|---|---|
| 1 | DOI 10.1002/jsfa.6319 | 6 | Approximation of diffusion (ADM) | 1 |
| 2 | 10.1081/DRT-120015577 | 3 | Page model | 1 |
| 3 | S0196-8904(02) 00099-7 | 8 | Logarithmic model | 1 |
| 4 | 10.1016/j.fbp.2011.02.008 | 4 | Midilli | 1 |
| 5 | 10.1016/j.biosystemseng.2004.07.011 | 11 | Logarithmic model | 2 |
| 6 | 10.1016/j.jfoodeng.2003.08.007 | 14 | Midilli | 2 |
| 7 | 10.1006/jaer.1997.0170 | 4 | Page model | 2 |
| 8 | 10.1016/S0260-8774(02)00065-1 | 14 | Logarithmic model | 3 |
| 9 | 10.1016/j.lwt.2008.01.003 | 8 | Thompson model | 1 |
| 10 | 10.1081/DRT-120015577 | 3 | Page model | 3 |
| 11 | 10.1016/j.lwt.2005.03.021 | 4 | Page Model | 4 |
| 12 | 10.1177/1082013211398832 | 10 | Page Model | 5 |
| 13 | 10.1177/1082013211398832 | 10 | Logarithmic model | 4 |
| 14 | 10.1016/j.jfoodeng.2004.02.001 | 12 | Approximation of diffusion (ADM) | 2 |
| 15 | 10.1016/j.jfoodeng.2006.01.057 | 11 | Midilli | 3 |
| 16 | 10.1016/j.biosystemseng.2006.05.001 | 6 | Page Model | 6 |
| 17 | 10.1016/j.jfoodeng.2005.12.044 | 3 | Logarithmic model | 5 |
| 18 | 10.1016/j.jfoodeng.2005.03.031 | 10 | Page Model | 7 |
| 19 | 10.1016/j.jfoodeng.2004.05.037 | 4 | Page Model | 8 |
| 20 | 10.1016/j.jfoodeng.2005.07.020 | 5 | Midilli | 4 |
| 21 | 10.1016/j.jfoodeng.2005.01.025 | 10 | Approximation of diffusion (ADM) | 3 |
| 22 | 10.1016/j.jfoodeng.2004.08.009 | 3 | Page Model | 9 |
| 23 | 10.1016/j.jfoodeng.2006.01.023 | 4 | Logarithmic model | 6 |
| 24 | 10.2202/1556-3758.1233 | 6 | Logarithmic model | 7 |
| 25 | 10.1016/S0260-8774(02)00386-2 | 2 | Page model | 10 |
| 26 | 10.1016/j.jfoodeng.2008.03.013 | 4 | Logarithmic model | 8 |
| 27 | 10.1081/DRT-120002553 | 2 | Page model | 11 |
| 28 | 10.1016/j.jfoodeng.2009.04.028 | 4 | Page Model | 12 |
| 29 | 10.1081/DRT-200054156 | 4 | Henderson Pabis | 1 |
| 30 | 10.1016/S0260-8774(02)00329-1 | 14 | Logarithmic model | 8 |
| 31 | 10.2202/1556-3758.1889 | 6 | Midilli | 5 |
| 32 | 10.1016/j.fbp.2009.09.004 | 3 | Page | 13 |
| 33 | 10.1016/j.biosystemseng.2006.12.009 | 3 | Two term exponential | 1 |
| 34 | 10.1016/j.fbp.2009.09.004 | 3 | Newton | 1 |
| 35 | 10.1016/j.biosystemseng.2006.12.009 | 3 | Newton | 2 |
| 36 | 10.1016/j.fbp.2009.09.004 | 3 | Logarithmic model | 9 |
| 37 | 10.1016/j.biosystemseng.2006.12.009 | 3 | Henderson Pabis | 2 |
| 38 | 10.1016/S0260-8774(98)00132-0 | 2 | Page Model | 14 |
| 39 | 10.1016/j.lwt.2010.10.003 | 3 | Approximation of diffusion (ADM) | 4 |
| 40 | 10.1080/07373930701372254 | 5 | Page Model | 15 |
| 41 | 10.1016/j.jfoodeng.2008.07.015 | 2 | Page Model | 16 |
| 42 | 10.1016/S0260-8774(02)00425-9 | 11 | Approximation of diffusion (ADM) | 5 |
| 43 | 10.1111/j.1750-3841.2006.00170.x | 9 | Exponential model | 1 |
| 44 | 10.1016/j.jfoodeng.2005.10.026 | 1 | Page Model | 16 |
| 45 | 10.1016/S0260-8774(01)00188-1 | 1 | Simplified Fick's diffusion model | 1 |
| 46 | 10.1016/j.cep.2008.10.004 | 1 | Simplified Fick's diffusion model | 2 |
| 47 | 10.1081/DRT-120025507 | 3 | Page Model | 17 |
| 48 | 10.1007/s13197-010-0217-8 | 4 | Logarithmic model | 9 |
| 49 | 10.1016/j.jfoodeng.2004.10.041 | 4 | Page Model | 18 |
| 50 | 10.1080/07373930802566077 | 5 | Logarithmic model | 10 |
| 51 | 10.1016/j.indcrop.2012.01.008 | 6 | Approximation of diffusion | 6 |
| 52 | 10.1016/j.biosystemseng.2005.11.010 | 4 | Page Model | 19 |

**APPENDIX B**

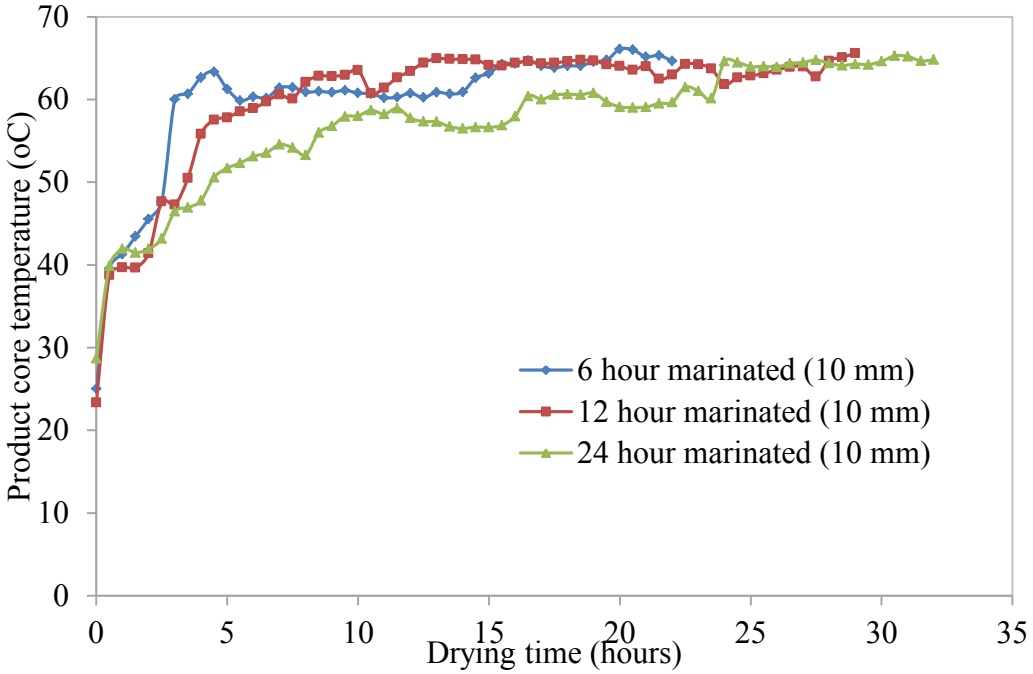


Figure 7.1 Variations of temperature with drying time for 10 mm thick biltong products dried under the HWL infrared heater

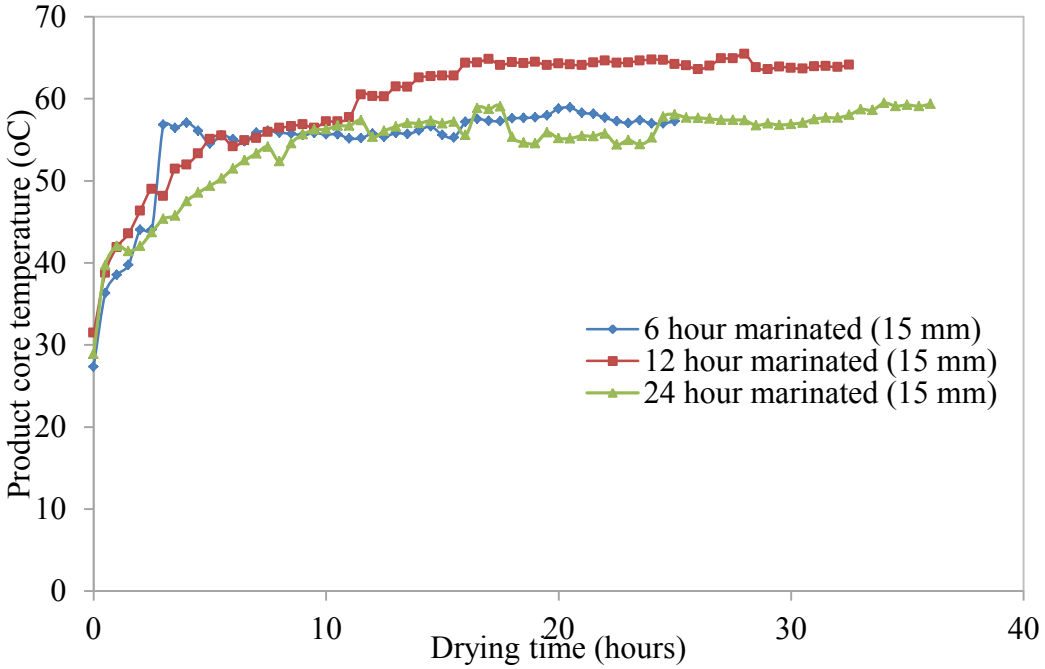


Figure 7.2 Variations of temperature with drying time for 15 mm thick biltong products dried under the HWL infrared heater

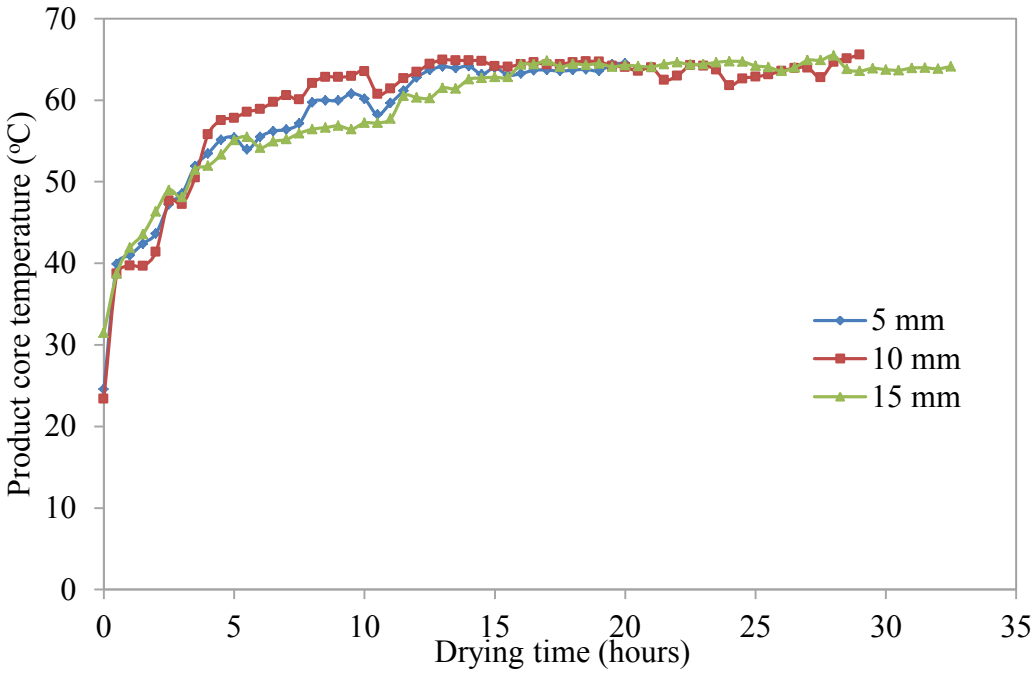


Figure 7.3 Variations of temperature with drying time for 12-hour marinated biltong products dried under the HWL infrared heater

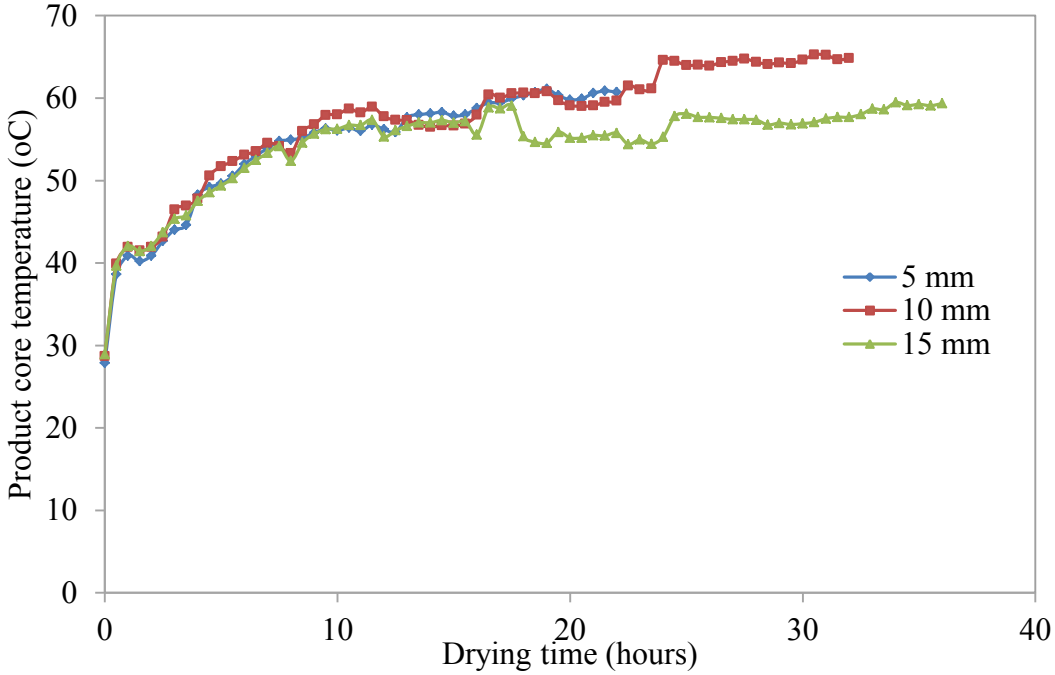


Figure 7.4 Variations of temperature with drying time for 24-hour marinated biltong products dried under the HWL infrared heater

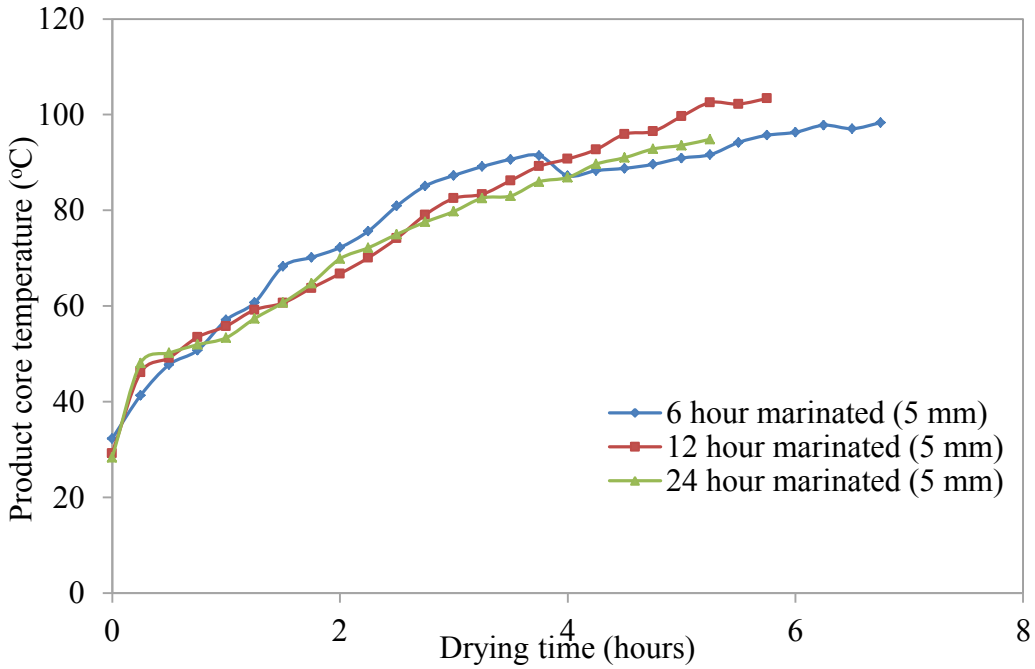


Figure 7.5 Variations of temperature with drying time for 5 mm thick biltong products dried under the LWL infrared heater

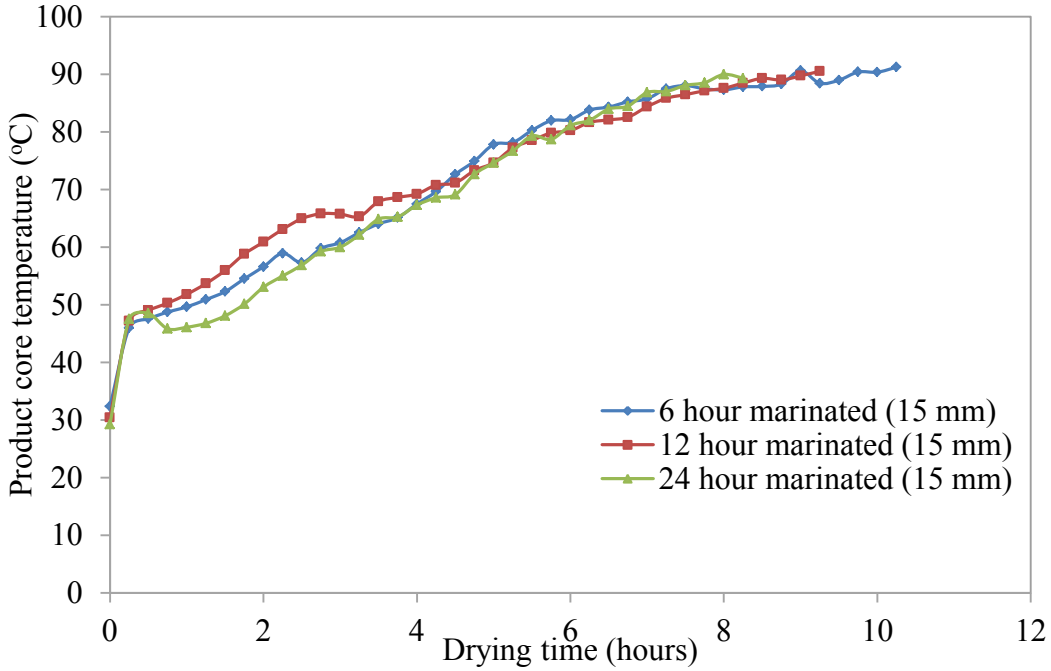


Figure 7.6 Variations of temperature with drying time for 15 mm thick biltong products dried under the LWL infrared heater

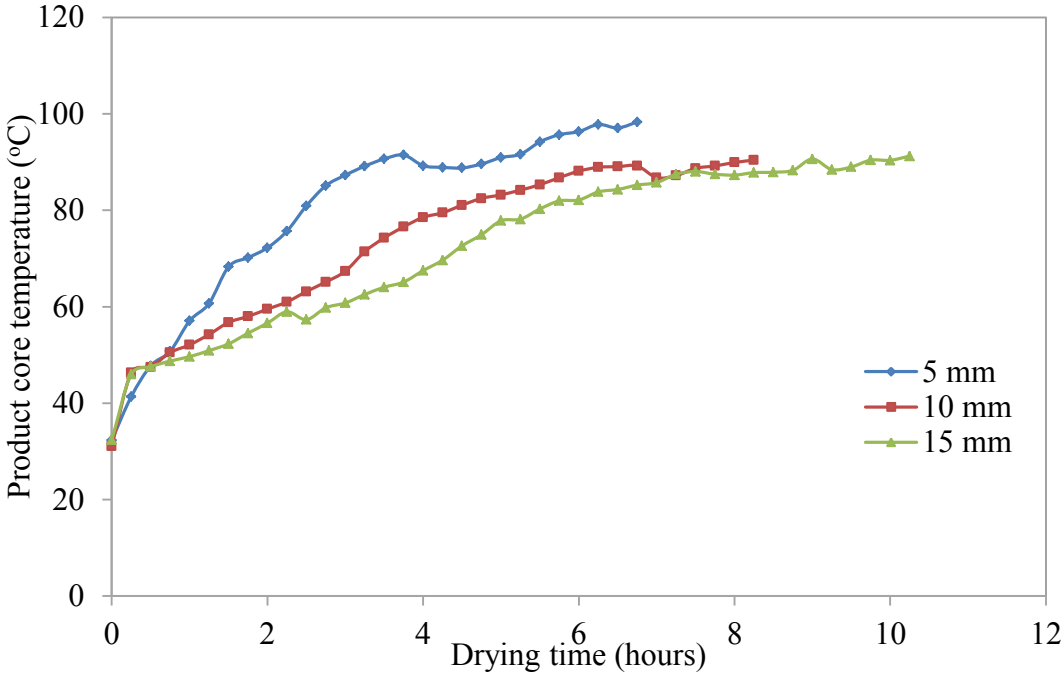


Figure 7.7 Variations of temperature with drying time for 6-hour marinated biltong products dried under the LWL infrared heater

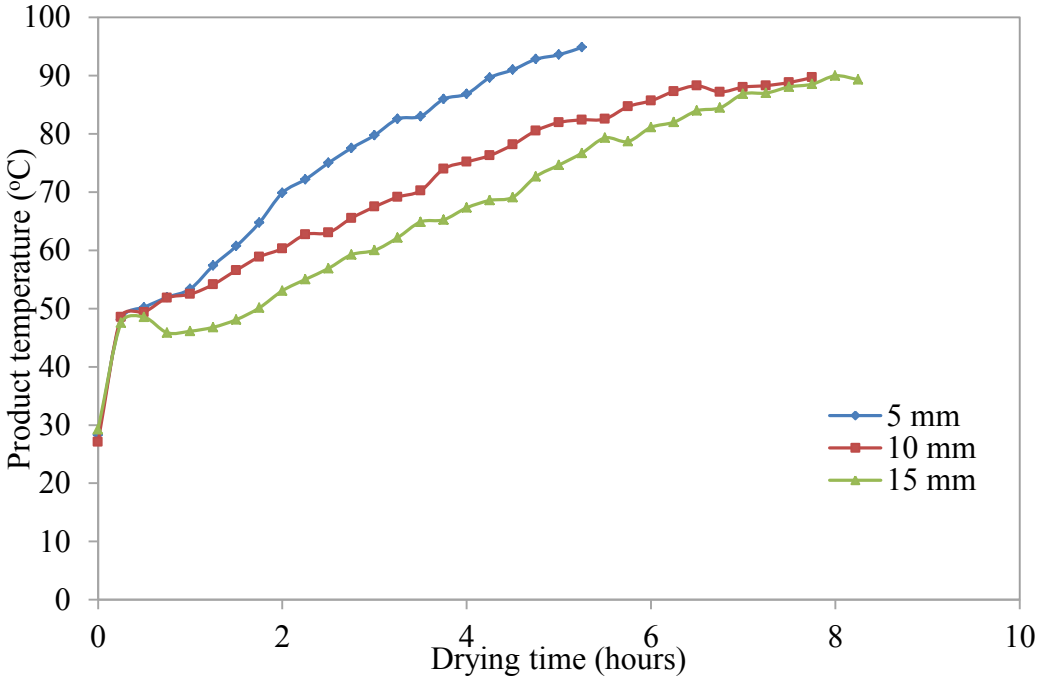


Figure 7.8 Variations of temperature with drying time for 6-hour marinated biltong products dried under the LWL infrared heater

**APPENDIX C**

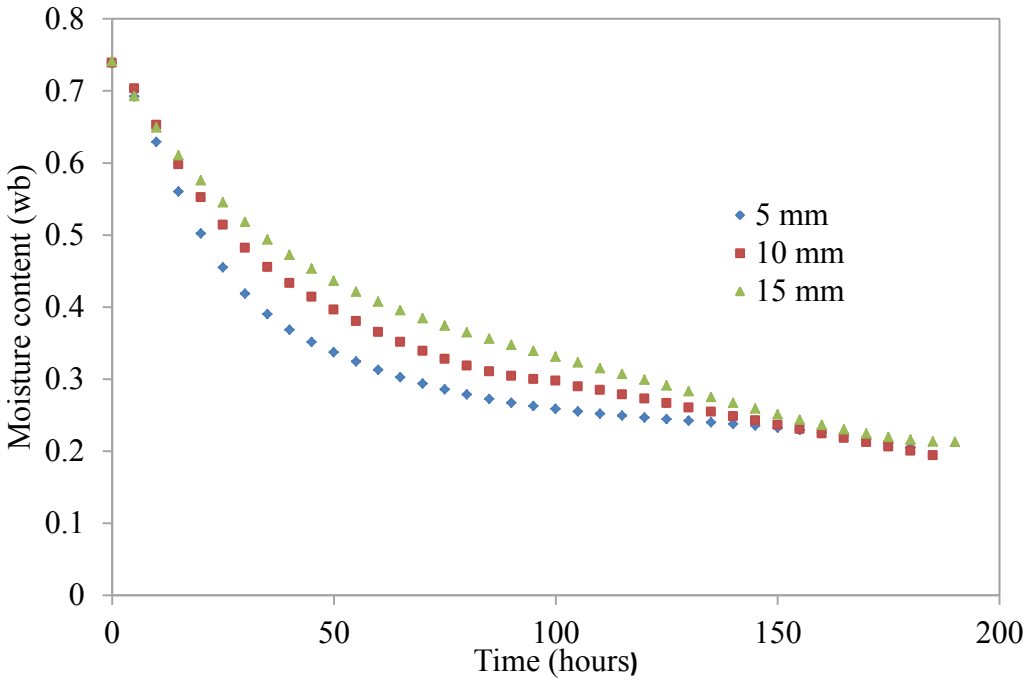


Figure 7.9 Variations in moisture content with drying time for 12-hour marinated biltong products dried under the convective air dryer

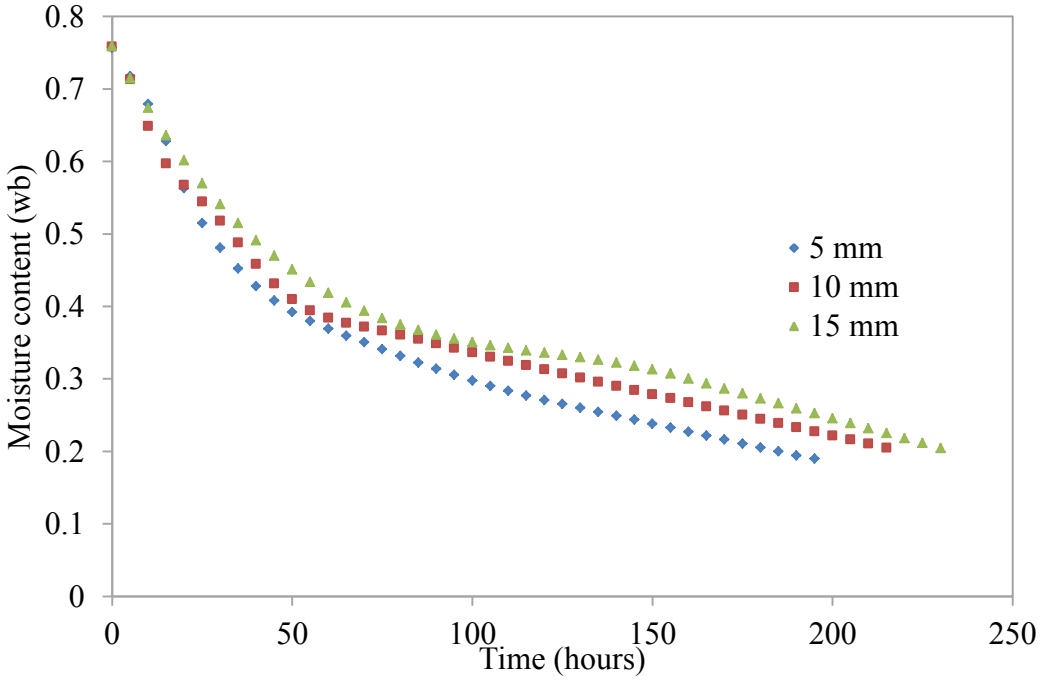


Figure 7.10 Variations in moisture content with drying time for 24-hour marinated biltong products dried under the convective air dryer

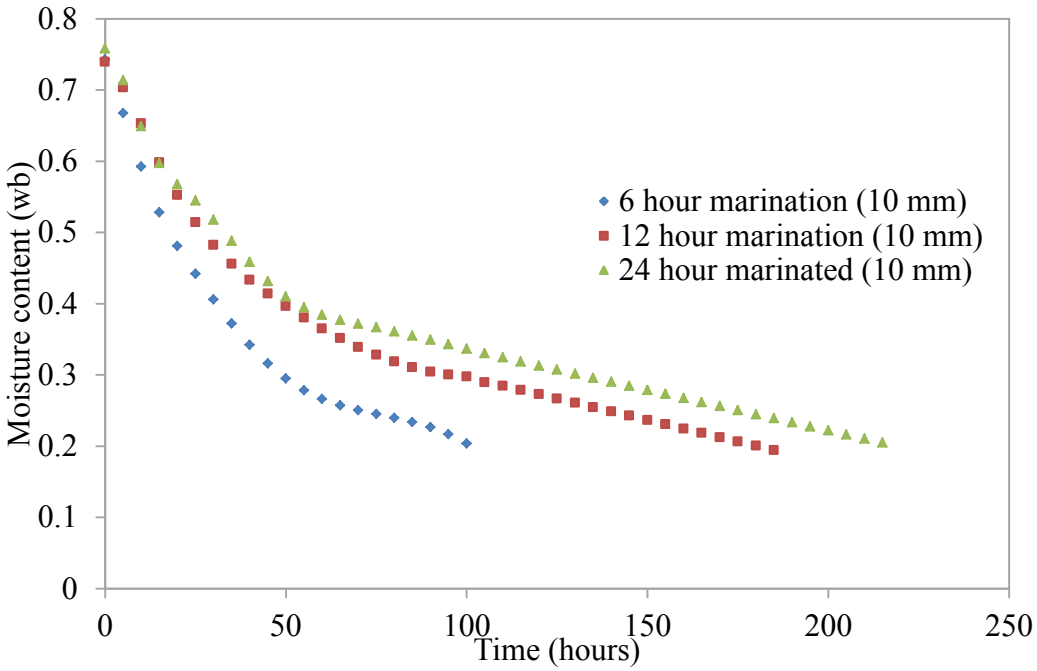


Figure 7.11 Variations in moisture content with drying time for 10 mm thick biltong products dried under the convective air dryer

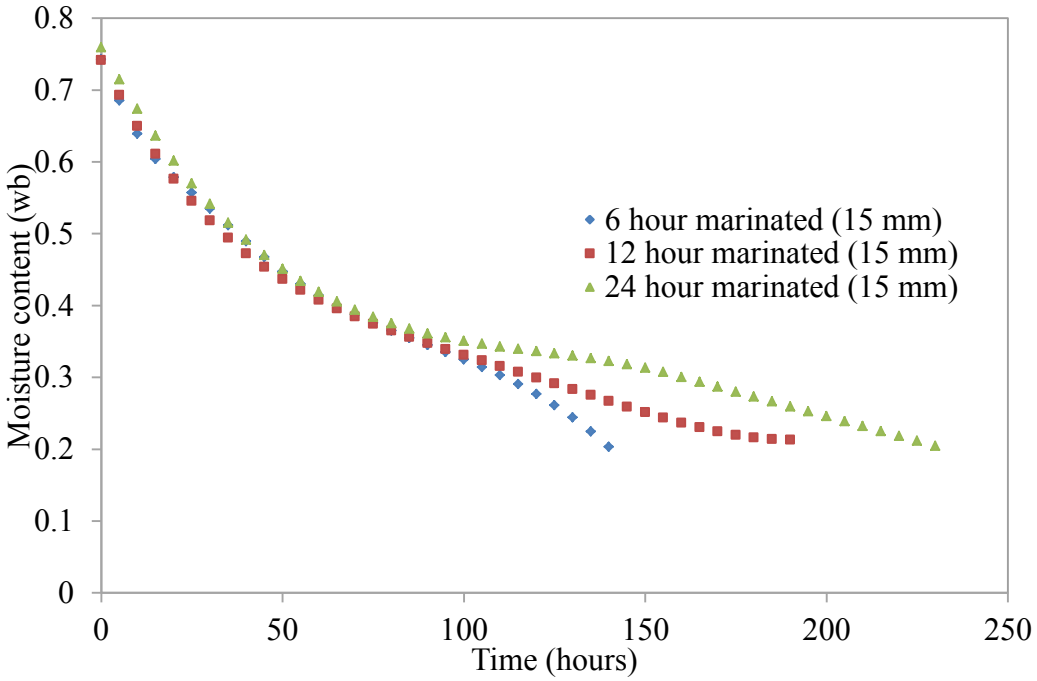


Figure 7.12 Variations in moisture content with drying time for 15 mm thick biltong products dried under the convective air dryer

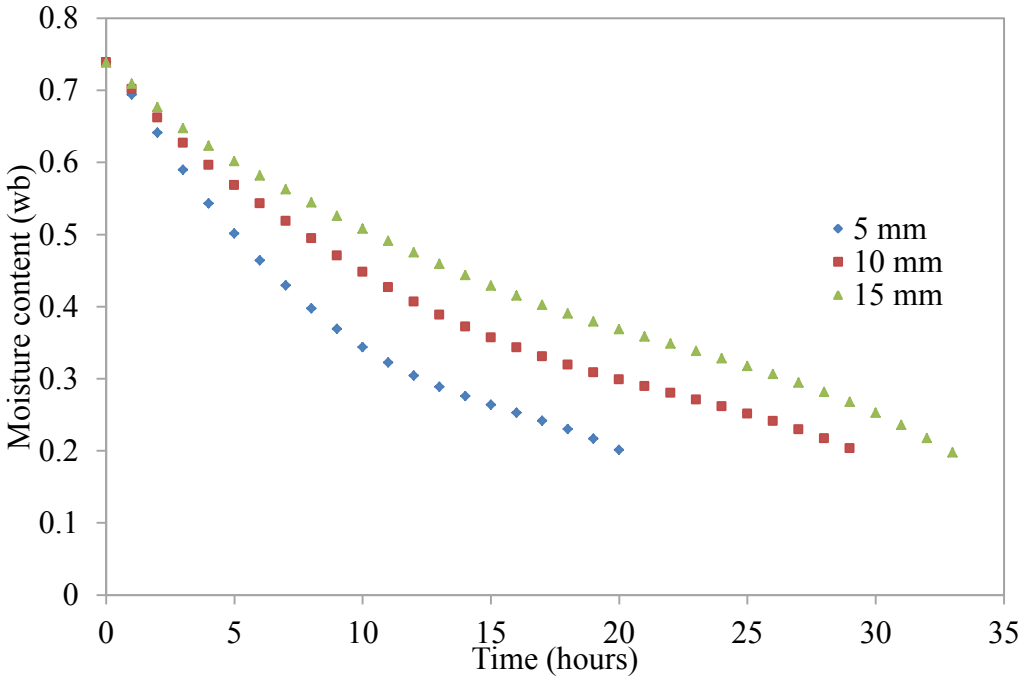


Figure 7.13 Variations in moisture content with drying time for 12-hour marinated biltong products dried under the HWL infrared heater

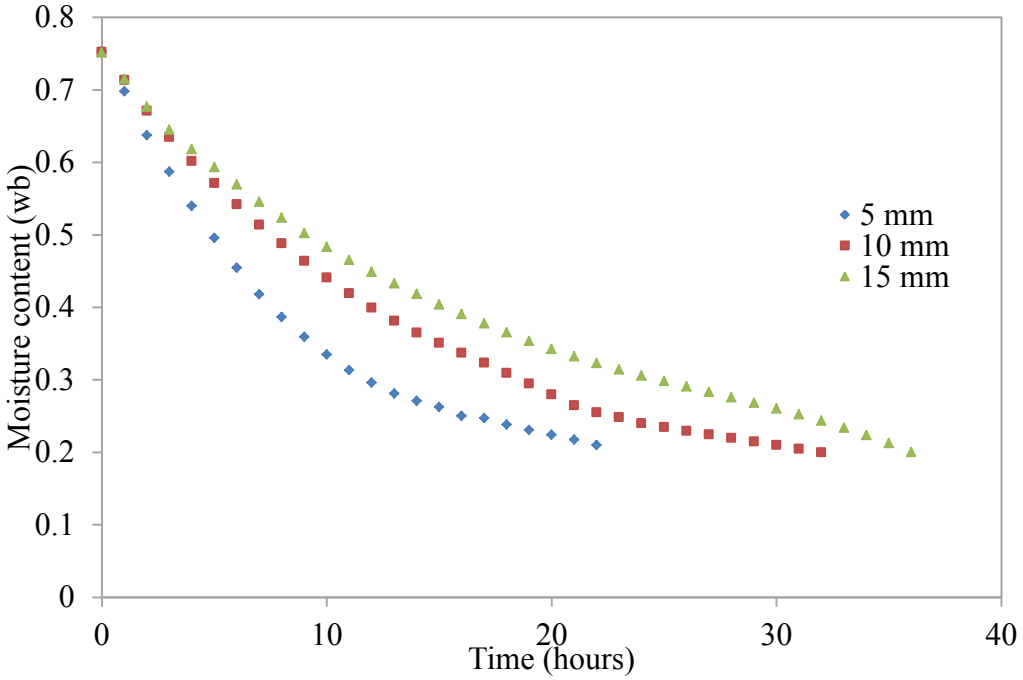


Figure 7.14 Variations in moisture content with drying time for 24-hour marinated biltong products dried under the HWL infrared heater

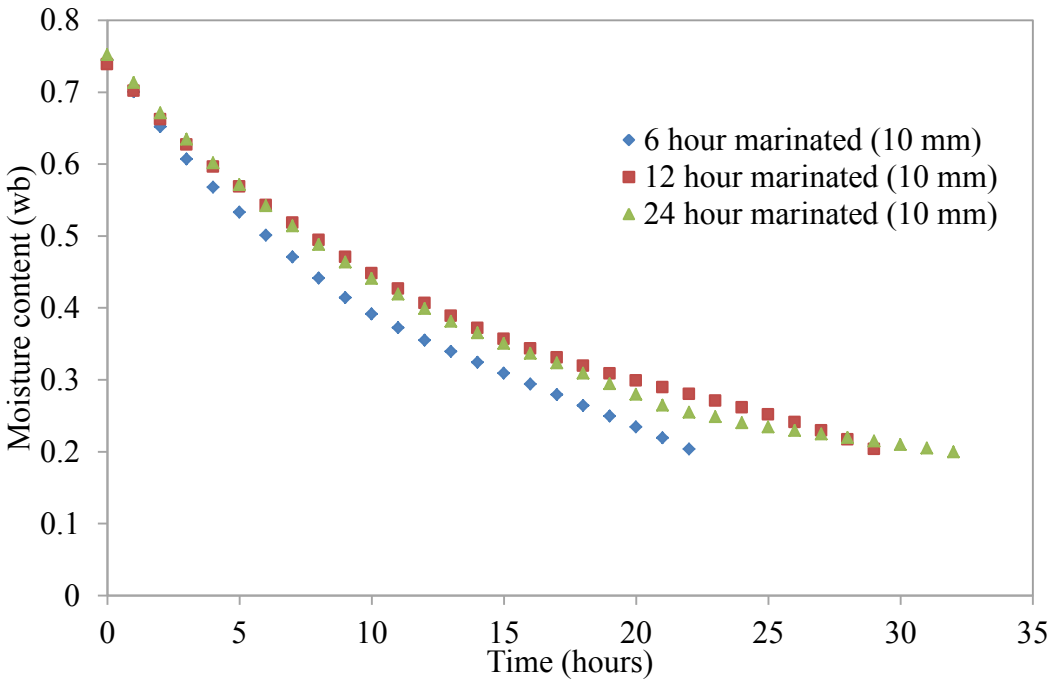


Figure 7.15 Variations in moisture content with drying time for 10 mm thick biltong products dried under the HWL infrared heater

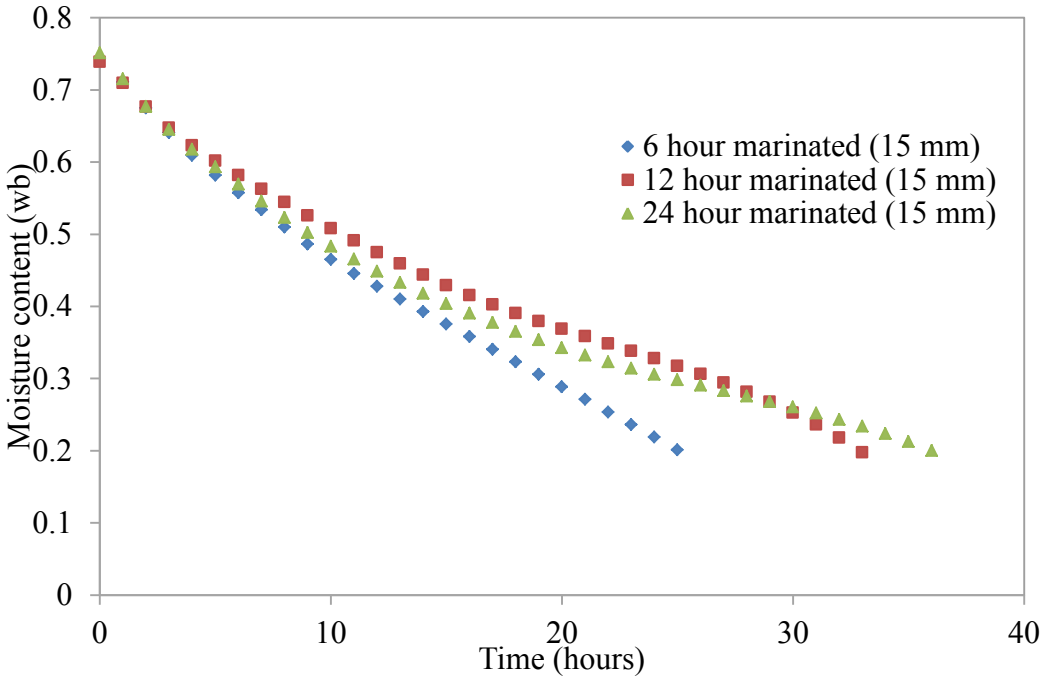


Figure 7.16 Variations in moisture content with drying time for 15 mm thick biltong products dried under the HWL infrared heater

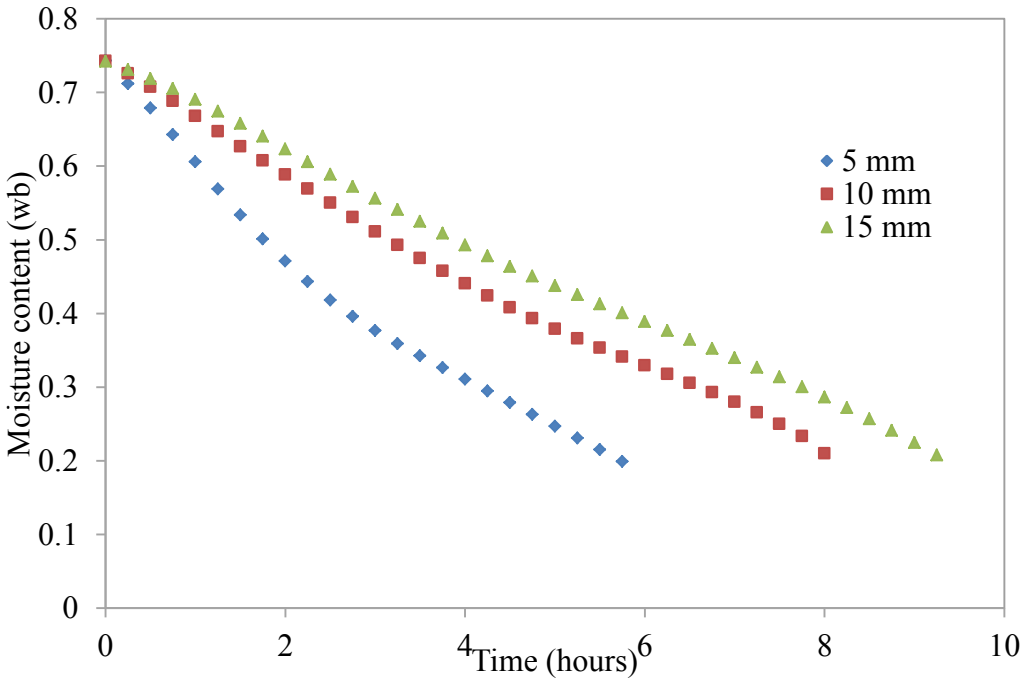


Figure 7.17 Variations in moisture content with drying time for 12-hour marinated biltong products dried under the LWL infrared heater

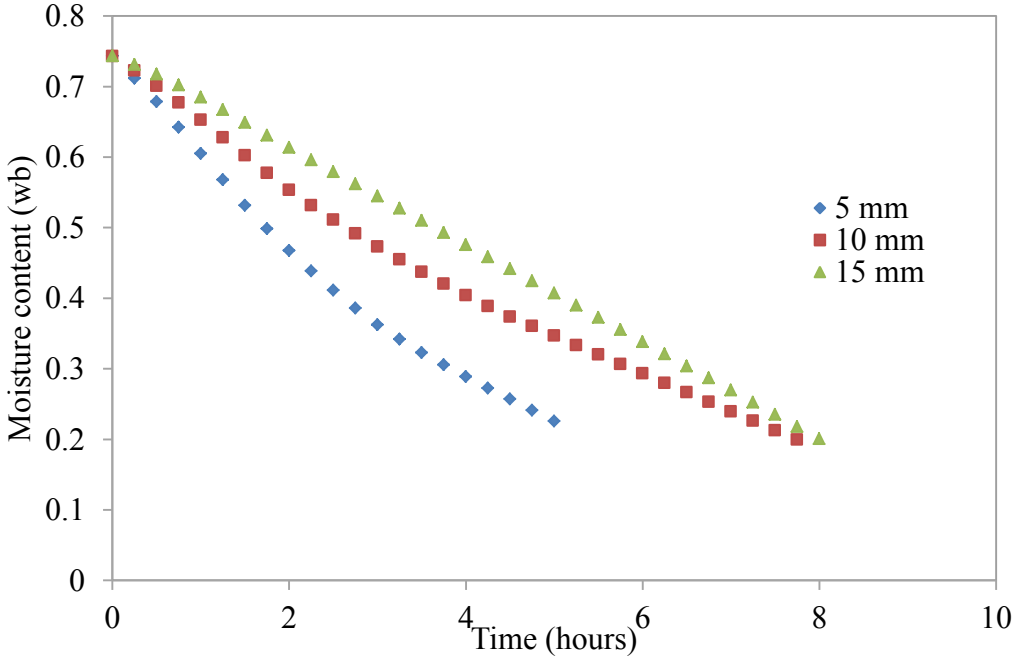


Figure 7.18 Variations in moisture content with drying time for 24-hour marinated biltong products dried under the LWL infrared heater

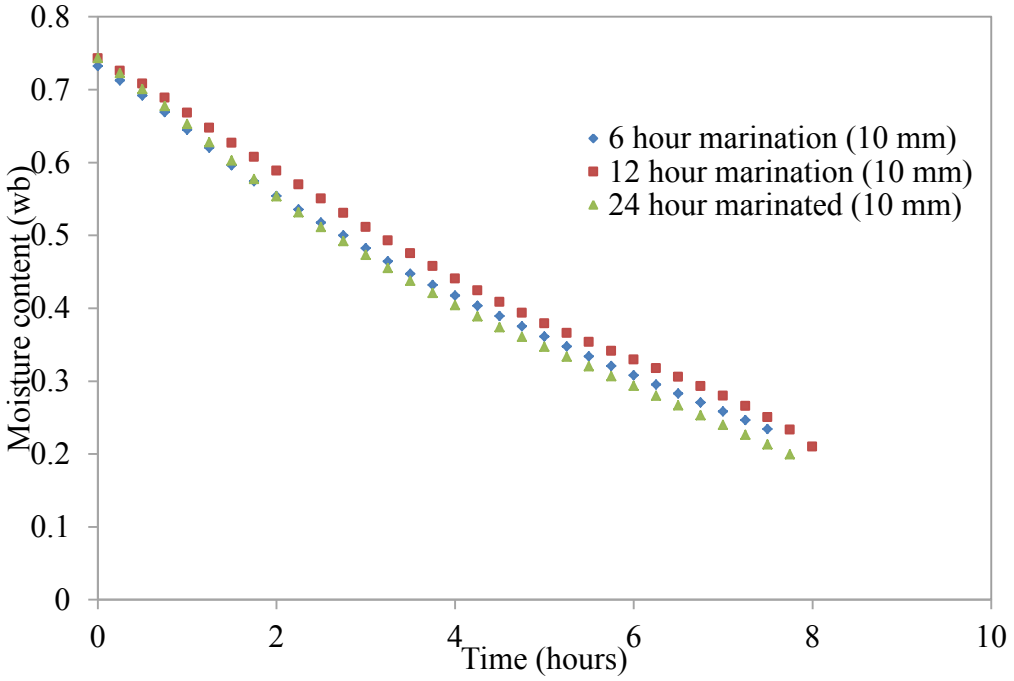


Figure 7.19 Variations in moisture content with drying time for 10 mm thick biltong products dried under the LWL infrared heater

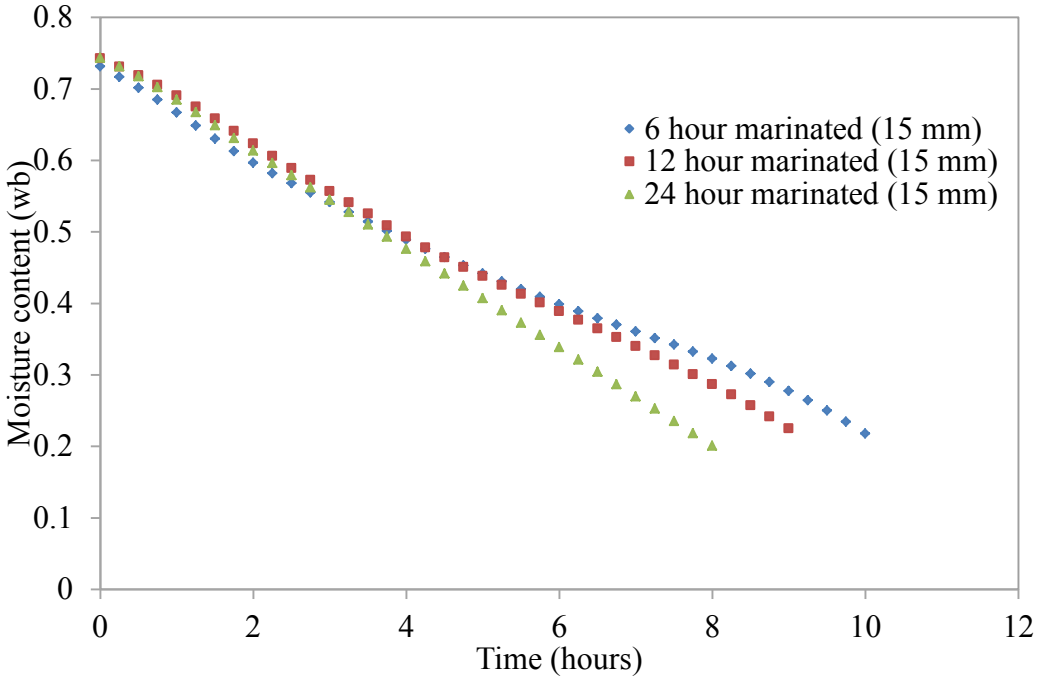


Figure 7.20 Variations in moisture content with drying time for 15 mm thick biltong products dried under the LWL infrared heater

**APPENDIX D**

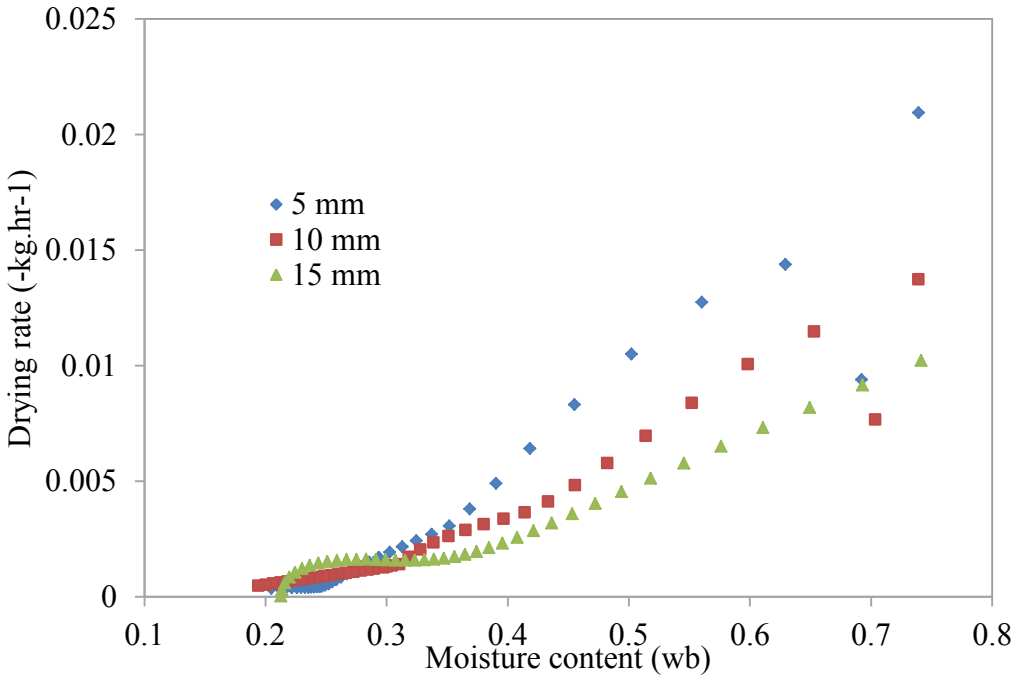


Figure 7.21 Variations in drying rate with moisture content for 12-hour marinated biltong products dried under the convective air dryer

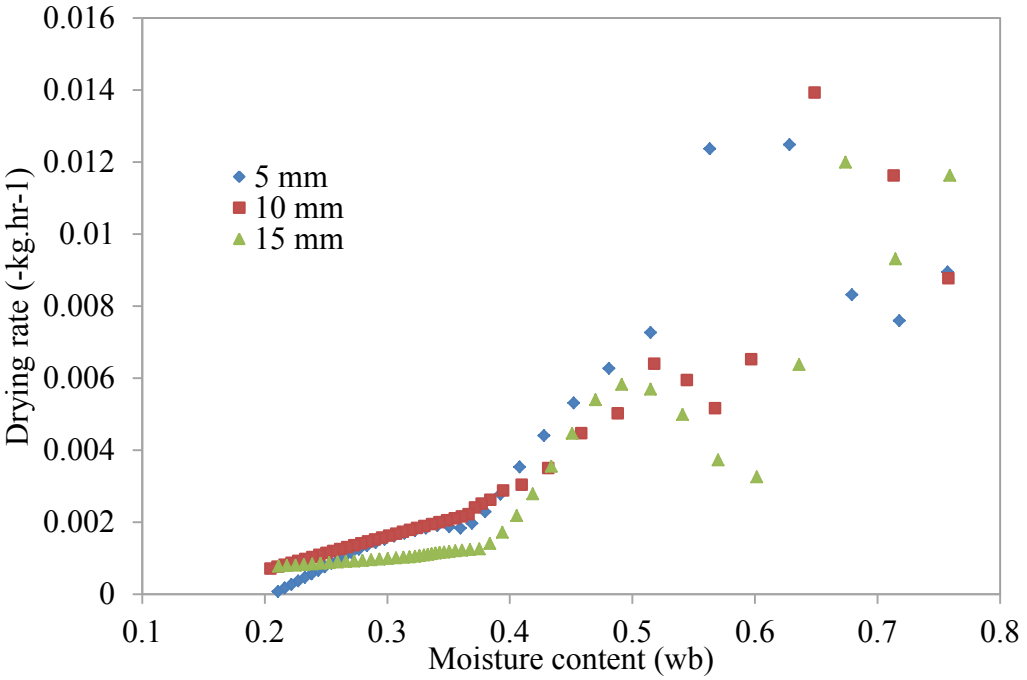


Figure 7.22 Variations in drying rate with moisture content for 24-hour marinated biltong products dried under the convective air dryer

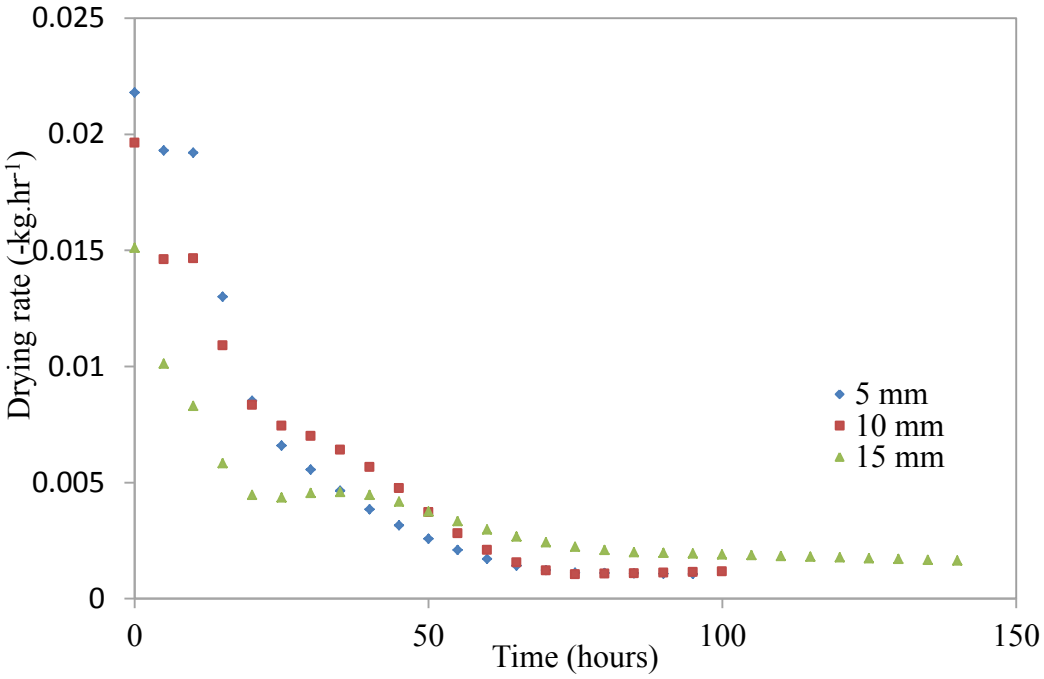


Figure 7.23 Variations in drying rate with drying time for 6-hour marinated biltong products dried under the convective air dryer

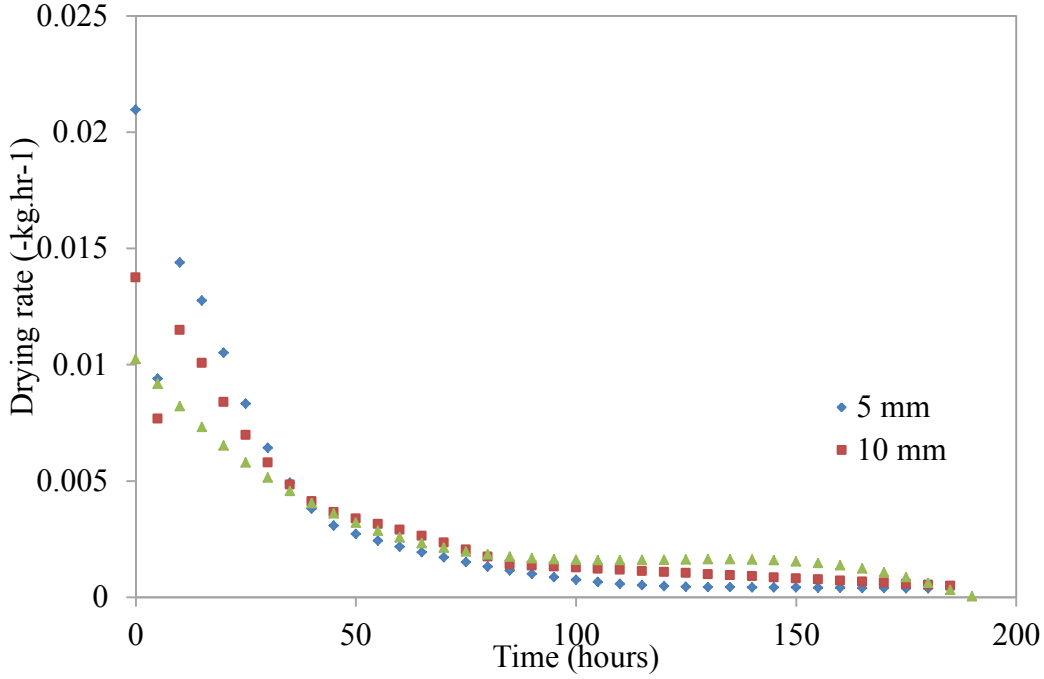


Figure 7.24 Variations in drying rate with drying time for 12-hour marinated biltong products dried under the convective air dryer

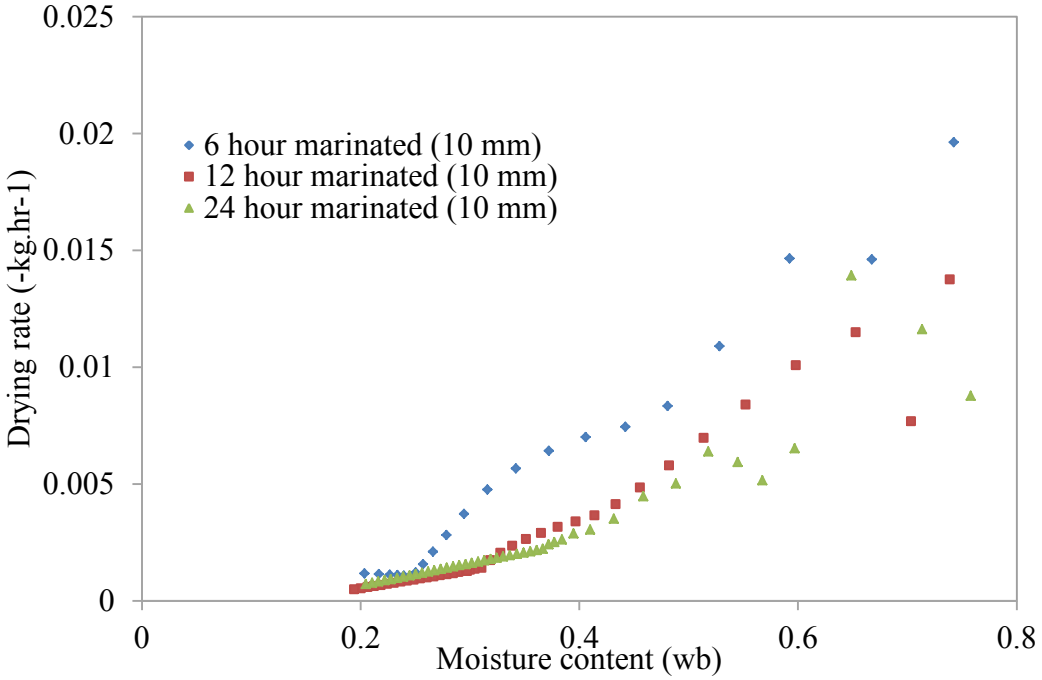


Figure 7.25 Variations in drying rate with moisture content for the 10 mm thick biltong products dried under the convective air dryer

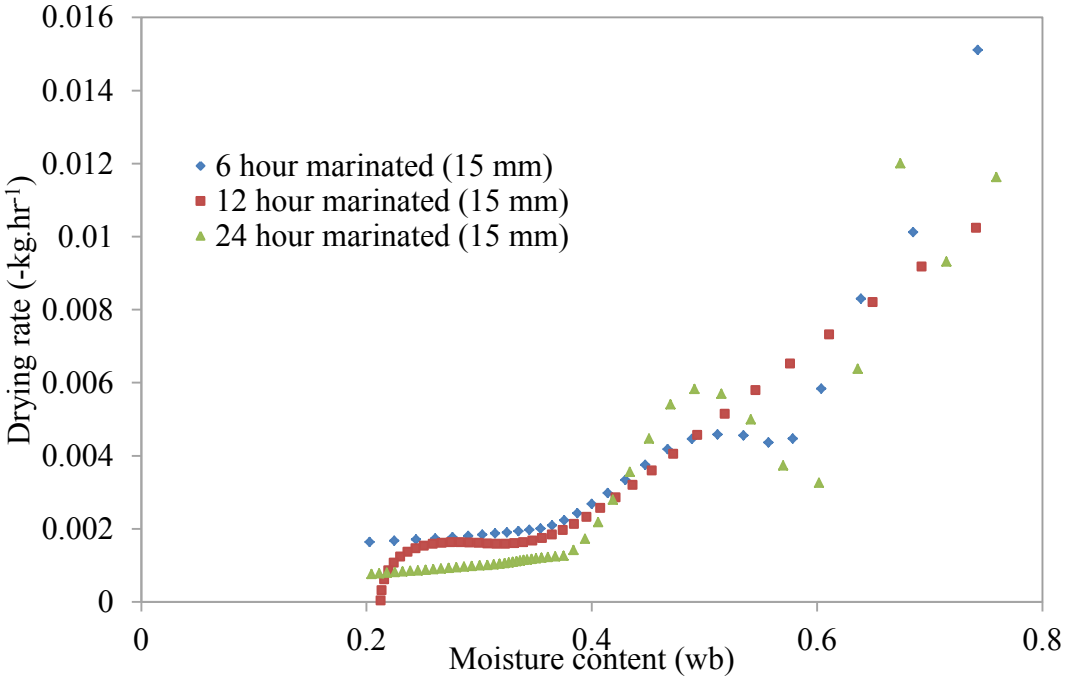


Figure 7.26 Variations in drying rate with moisture content for the 15 mm thick biltong products dried under the convective air dryer

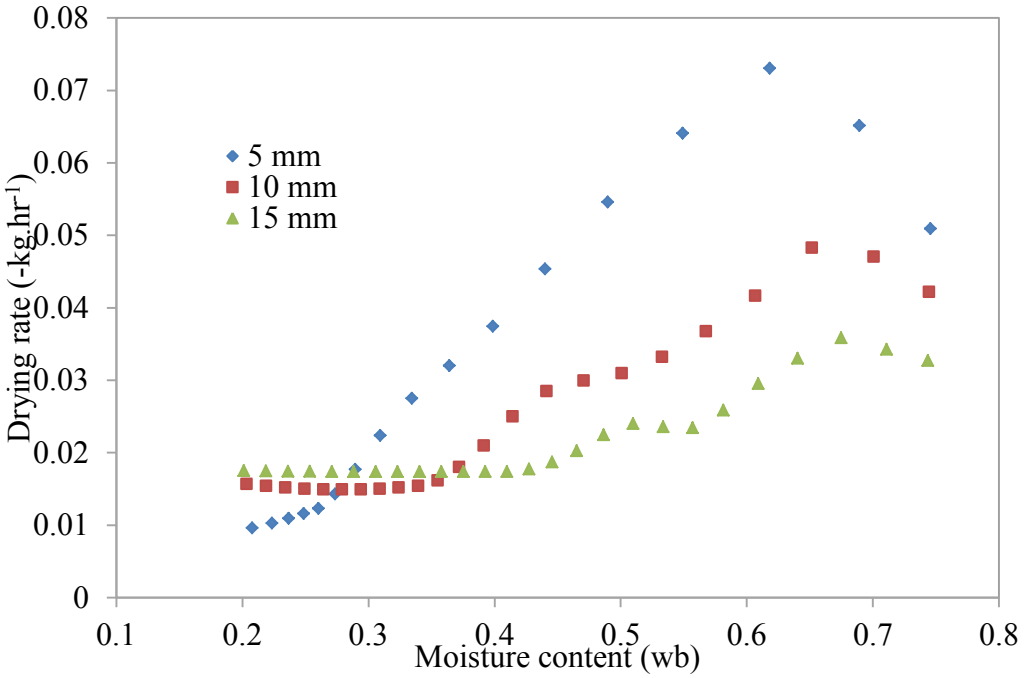


Figure 7.27 Variations in drying rate with moisture content for 6-hour marinated biltong products dried under the HWL infrared heater

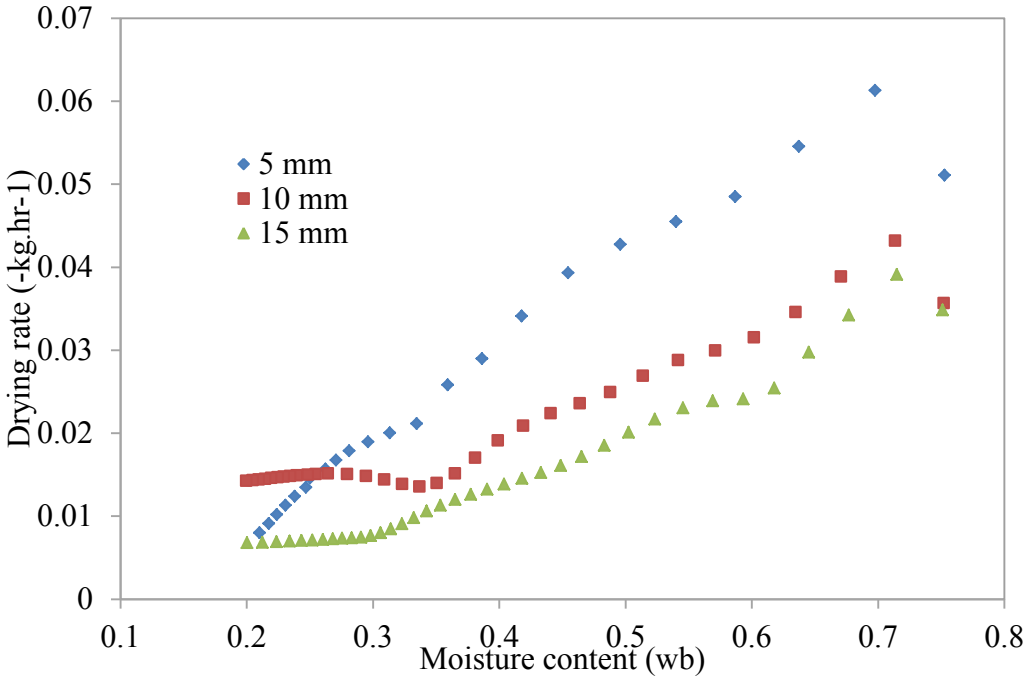


Figure 7.28 Variations in drying rate with moisture content for 24-hour marinated biltong products dried under the HWL infrared heater

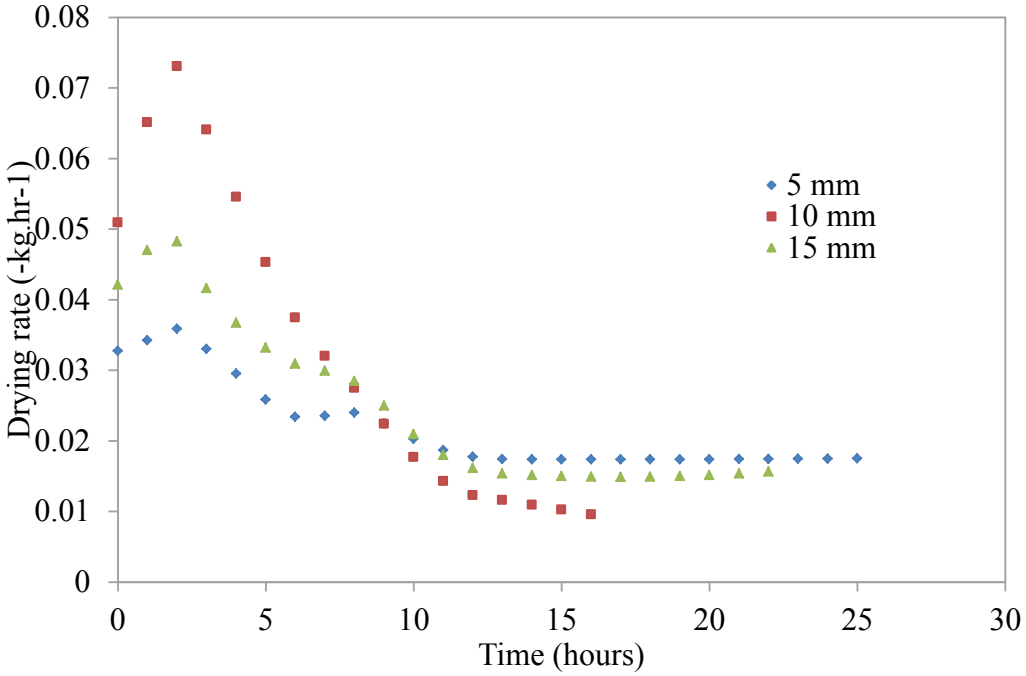


Figure 7.29 Variations in drying rate with drying time for 6-hour marinated biltong products dried under the HWL infrared heater

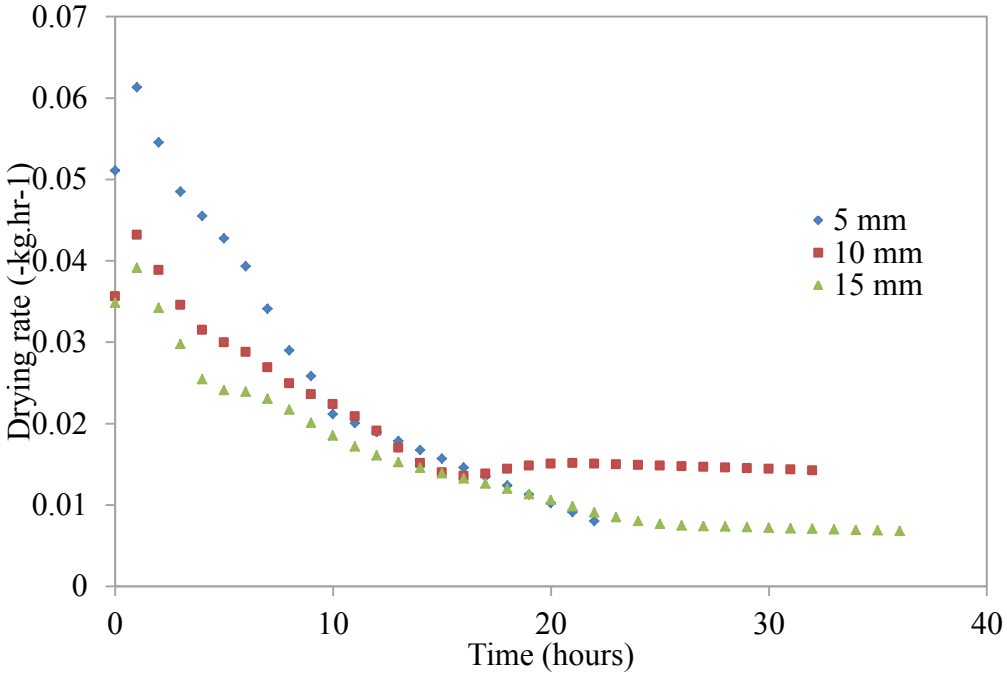


Figure 7.30 Variations in drying rate with drying time for 24-hour marinated biltong products dried under the HWL infrared heater

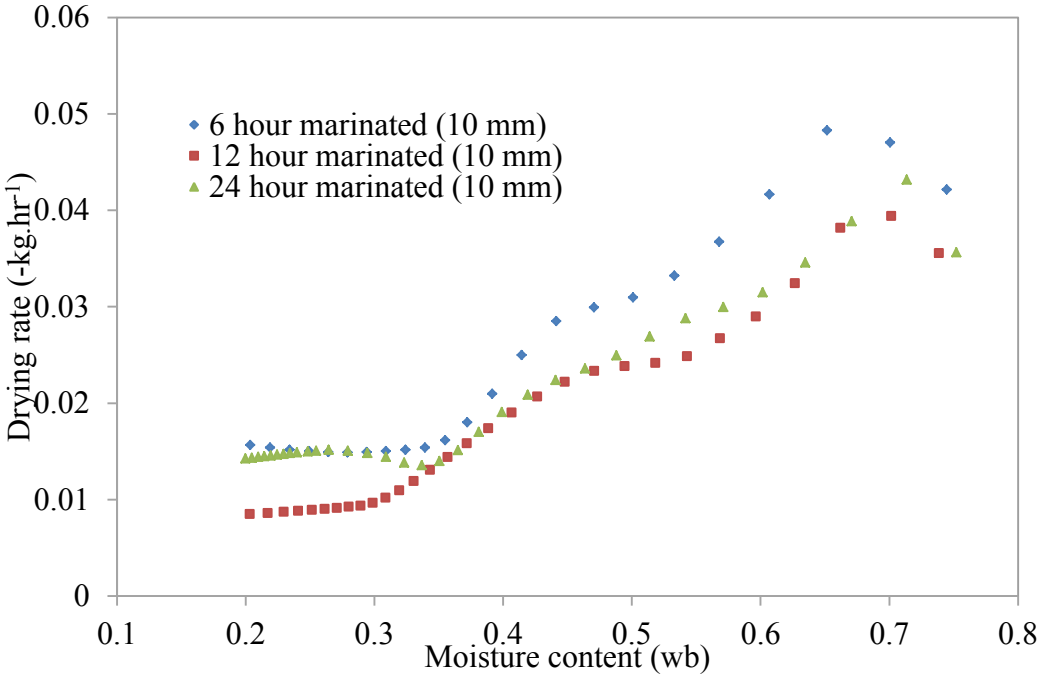


Figure 7.31 Variations in drying rate with moisture content for the 10 mm thick biltong products dried under the HWL infrared heater

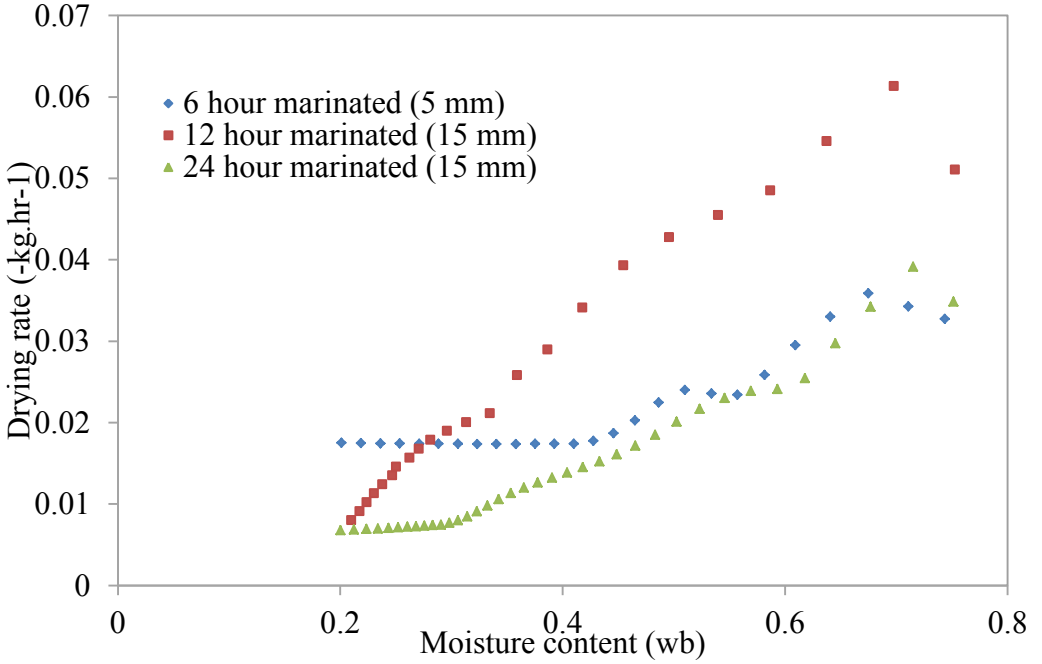


Figure 7.31 Variations in drying rate with moisture content for the 5 mm thick biltong products dried under the HWL infrared heater

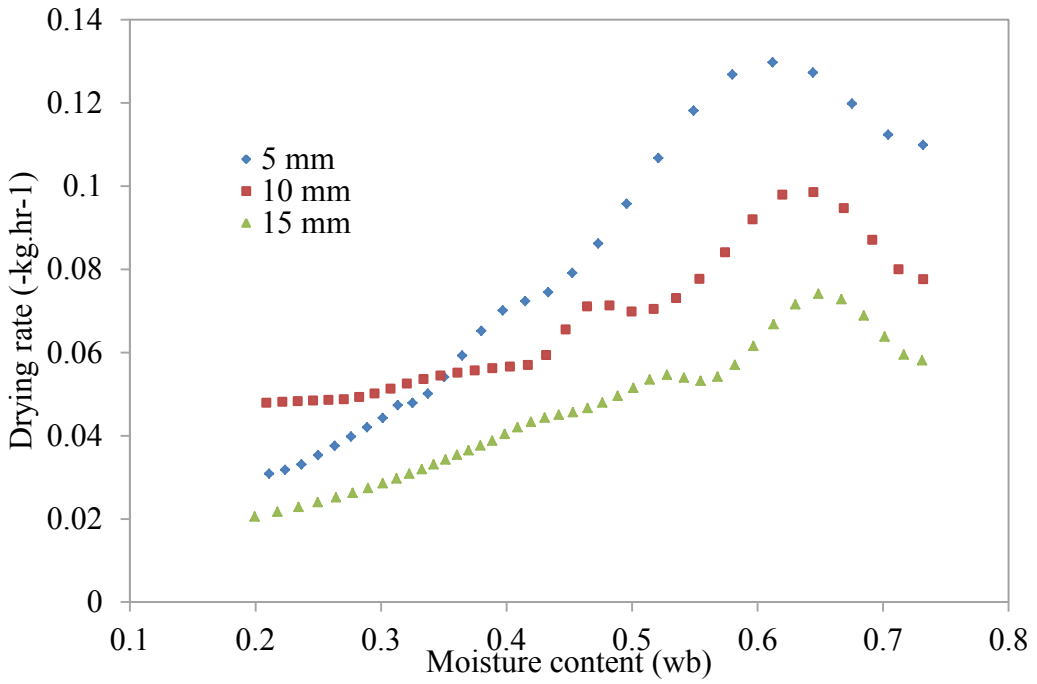


Figure 7.32 Variations in drying rate with moisture content for 6-hour marinated biltong products dried under the LWL infrared heater

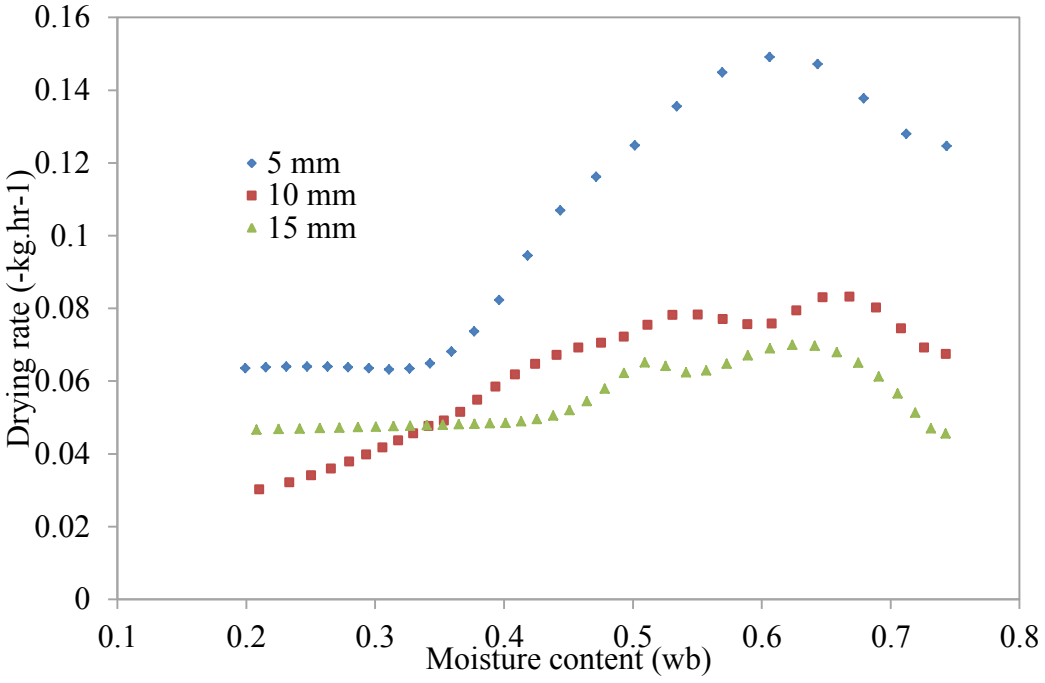


Figure 7.33 Variations in drying rate with moisture content for 24-hour marinated biltong products dried under the LWL infrared heater

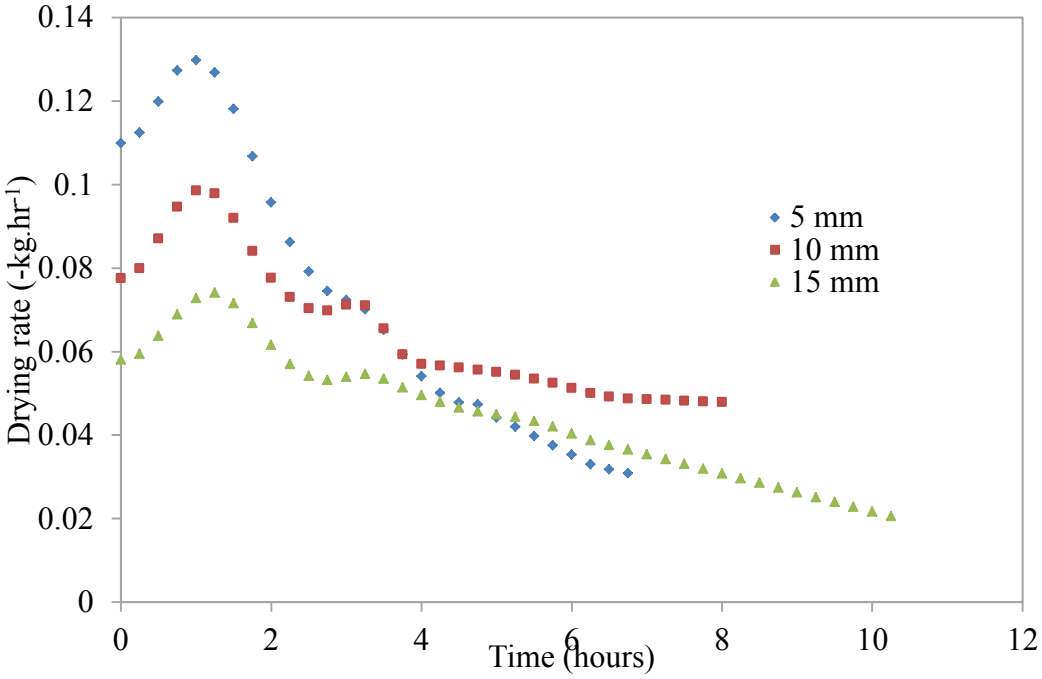


Figure 7.34 Variations in drying rate with drying time for 6-hour marinated biltong products dried under the LWL infrared heater

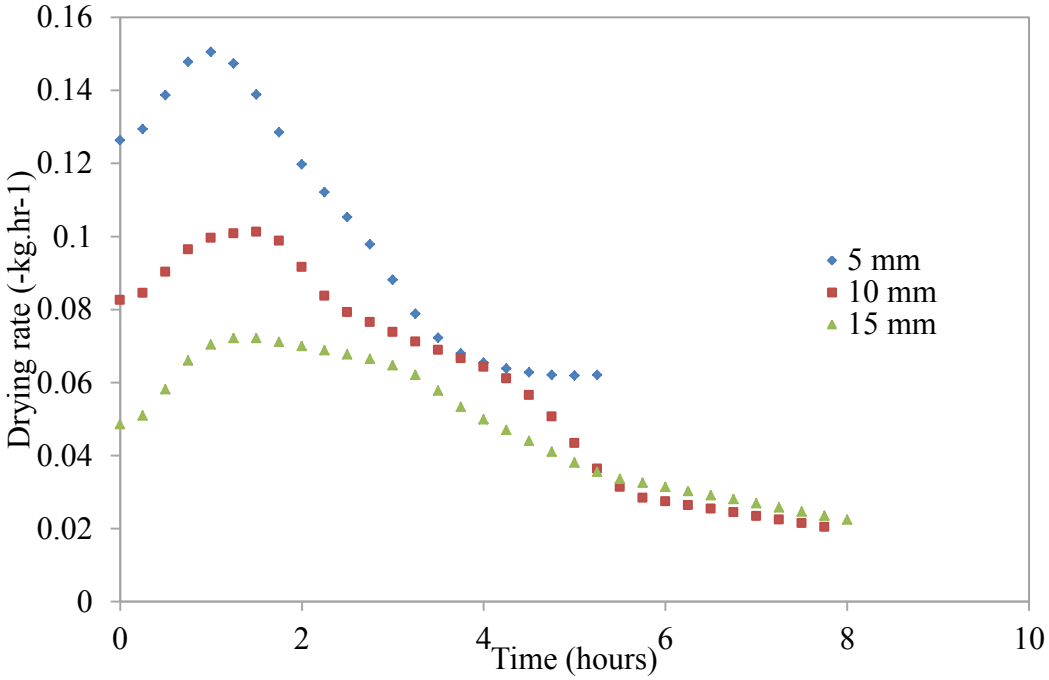


Figure 7.35 Variations in drying rate with drying time for 24-hour marinated biltong products dried under the LWL infrared heater

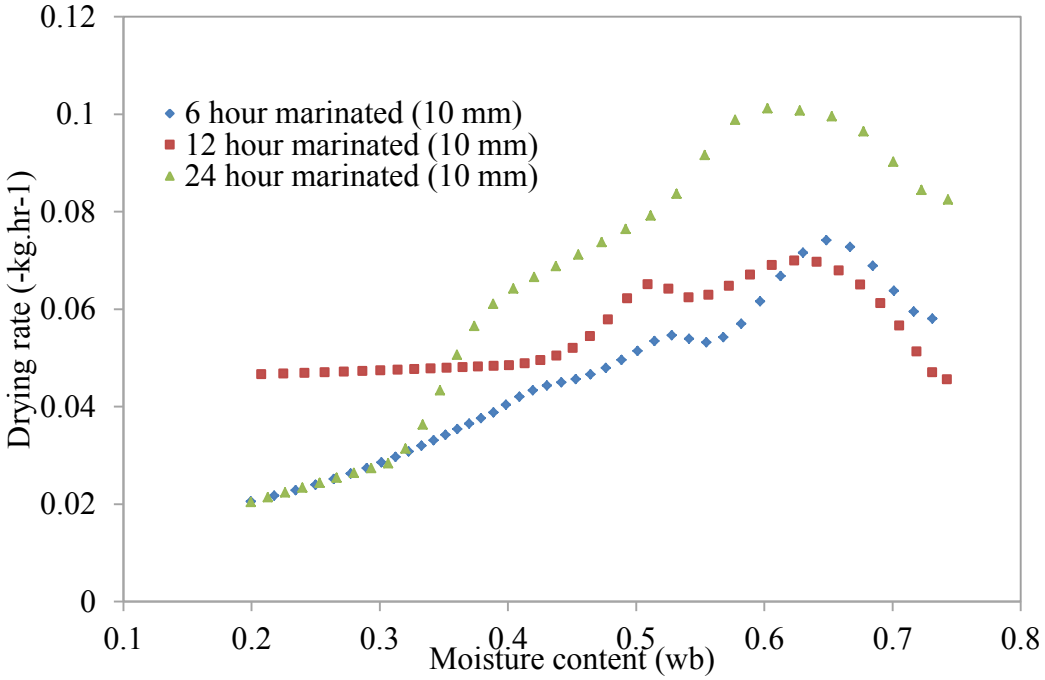


Figure 7.36 Variations in drying rate with moisture content for the 10 mm thick biltong products dried under the LWL infrared heater

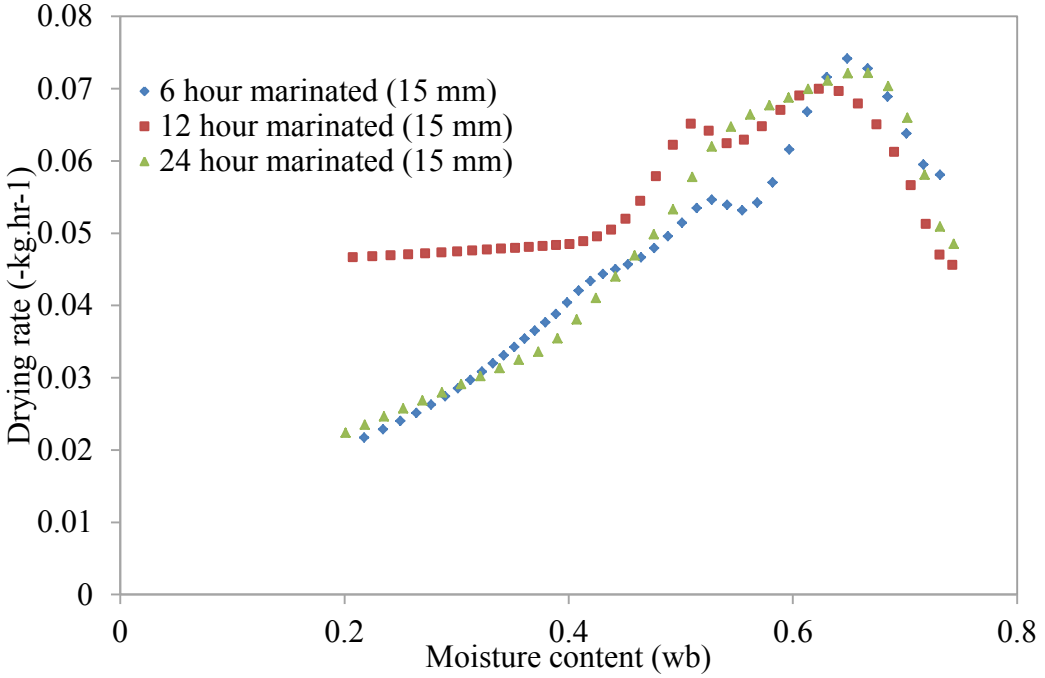


Figure 7.37 Variations in drying rate with moisture content for the 15 mm thick biltong products dried under the LWL infrared heater

**APPENDIX E**

Table 7.2 Lightness (L*) ANOVA table

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Dryer | 128.355 | 2 | 64.178 | 7.933 | 0.003** |
| Marination | 17.921 | 2 | 8.961 | 1.108 | 0.352 |
| Thickness | 52.007 | 2 | 26.004 | 4.143 | 0.033** |
| Dryer * Marination | 12.904 | 4 | 3.226 | 0.399 | 0.807 |
| Dryer * Thickness | 11.447 | 4 | 2.862 | 0.456 | 0.767 |
| Thickness * Marination | 12.545 | 4 | 3.136 | 0.254 | 0.903 |
| Dryer * Marination* Thickness | 82.473 | 8 | 10.309 | 0.835 | 0.584 |
| Error | 145.617 | 18 | 8.090 | | |
| Total | 15172.339 | 27 | | | |
| Corrected Total | 304.797 | 26 | | | |

Table 7.3 Redness (a*) ANOVA table

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Dryer | 11.726 | 2 | 5.863 | 1.614 | 0.227 |
| Marination | 4.662 | 2 | 2.331 | 0.642 | 0.538 |
| Thickness | 34.372 | 2 | 17.186 | 5.591 | 0.013** |
| Dryer * Marination | 20.714 | 4 | 5.179 | 1.425 | 0.266 |
| Dryer * Thickness | 1.071 | 4 | 0.268 | 0.087 | 0.985 |
| Thickness * Marination | 5.584 | 4 | 1.396 | 0.434 | 0.782 |
| Dryer * Marination* Thickness | 44.617 | 8 | 5.577 | 1.734 | 0.158 |
| Error | 57.880 | 18 | 3.216 | | |
| Total | 2082.768 | 27 | | | |
| Corrected Total | 102.497 | 26 | | | |

Table 7.4 Yellowness (b*) ANOVA table

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Dryer | 54.841 | 2 | 27.420 | 2.965 | 0.077 |
| Marination | 9.259 | 2 | 4.629 | 0.501 | 0.614 |
| Thickness | 97.073 | 2 | 48.537 | 7.739 | 0.004** |
| Dryer * Marination | 41.665 | 4 | 10.416 | 1.126 | 0.375 |
| Dryer * Thickness | 7.436 | 4 | 1.859 | 0.296 | 0.876 |
| Thickness * Marination | 10.224 | 4 | 2.556 | 0.296 | 0.877 |
| Dryer * Marination* Thickness | 116.556 | 8 | 14.570 | 1.685 | 0.170 |
| Error | 155.679 | 18 | 8.649 | | |
| Total | 3034.794 | 27 | | | |
| Corrected Total | 272.236 | 26 | | | |

Table 7.5 Total colour difference (ΔE) ANOVA table

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Dryer | 359.537 | 2 | 179.769 | 8.558 | 0.002** |
| Marination | 30.140 | 2 | 15.070 | 0.717 | 0.501 |
| Thickness | 2.842 | 2 | 1.421 | 0.058 | 0.944 |
| Dryer * Marination | 375.192 | 4 | 93.798 | 4.465 | 0.011** |
| Dryer * Thickness | 340.770 | 4 | 85.193 | 3.487 | 0.028** |
| Thickness * Marination | 8.393 | 4 | 2.098 | 0.034 | 0.998 |
| Dryer * Marination* Thickness | 41.375 | 8 | 5.172 | 0.085 | 0.999 |
| Error | 1101.584 | 18 | 61.199 | | |
| Total | 7872.452 | 27 | | | |
| Corrected Total | 1142.959 | 26 | | | |

** Significant at p=0.05

## APPENDIX F

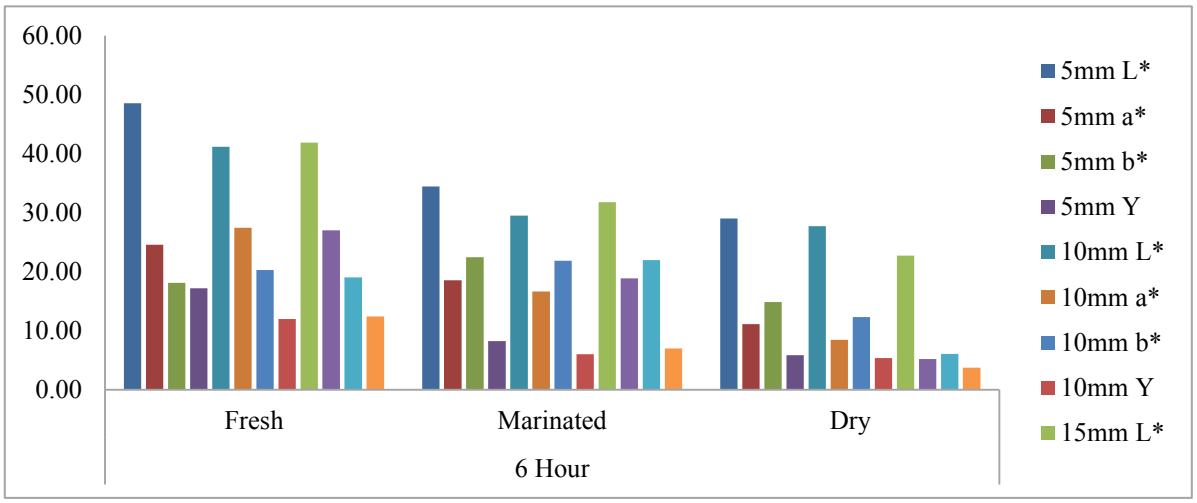


Figure 3.8 Changes in colour attributes of 6-hour marinated convective air dried biltong samples during different stages of processing

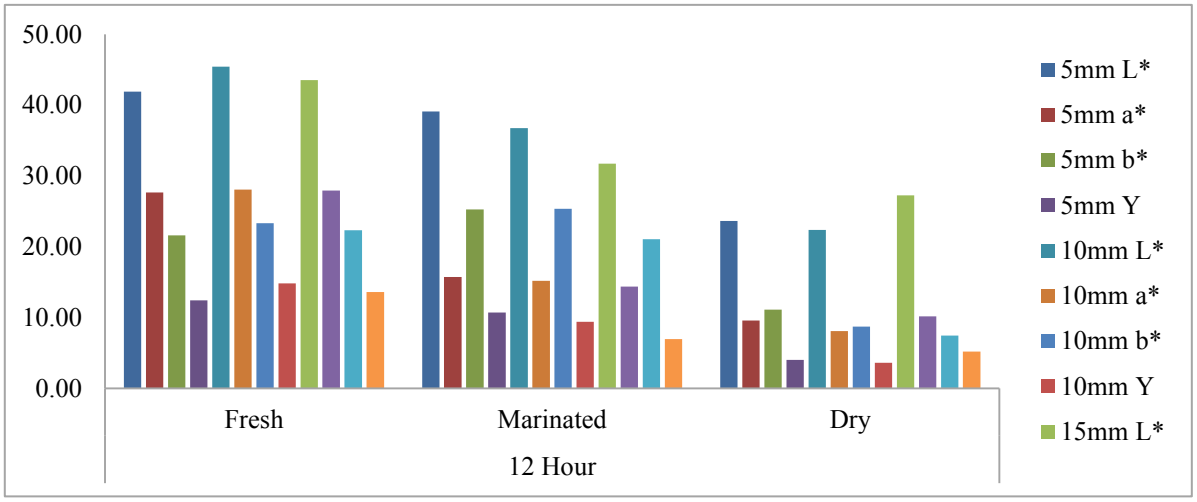


Figure 3.9 Changes in colour attributes of 12-hour marinated convective air dried biltong samples during different stages of processing

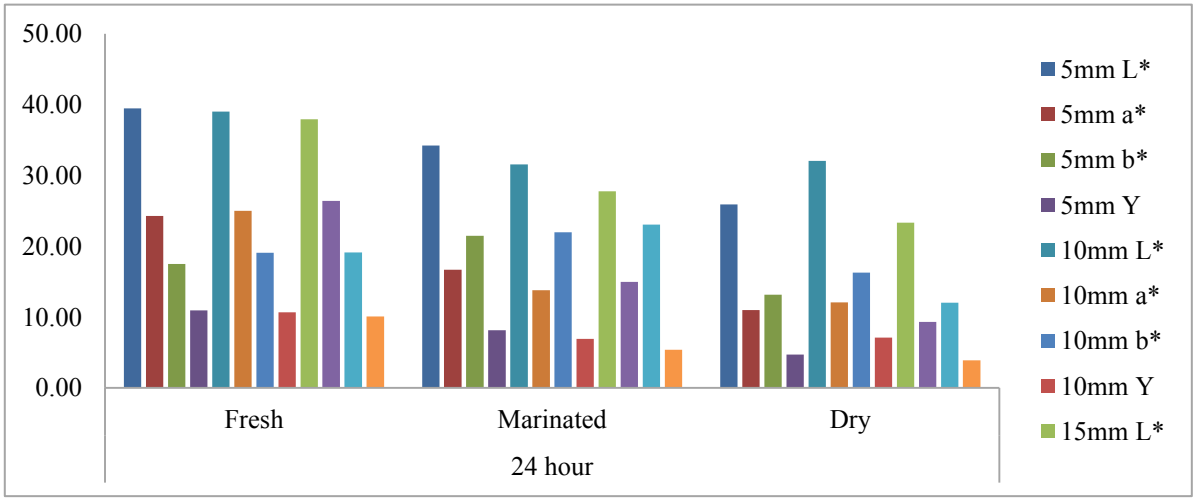


Figure 7.40 Changes in colour attributes of 24-hour marinated convective air dried biltong samples during different stages of processing

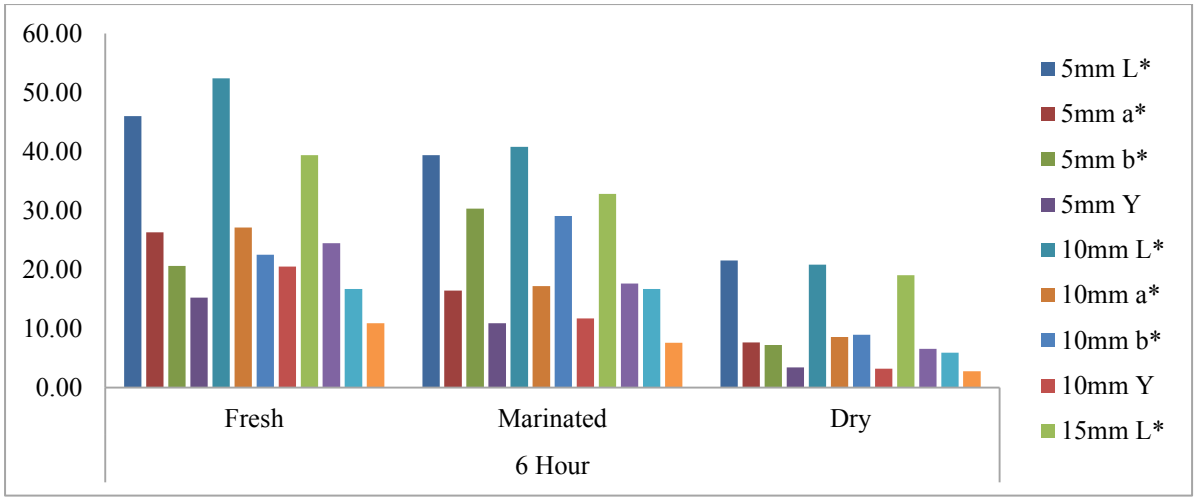


Figure 7.41 Changes in colour attributes of 6-hour marinated HWL infrared dried biltong samples during different stages of processing

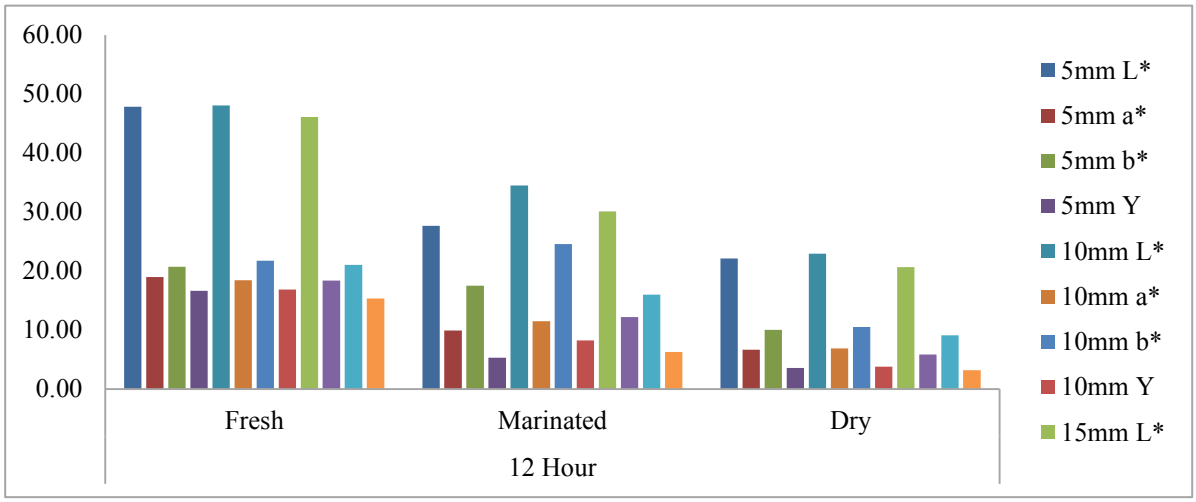


Figure 7.42 Changes in colour attributes of 12-hour marinated HWL infrared dried biltong samples during different stages of processing

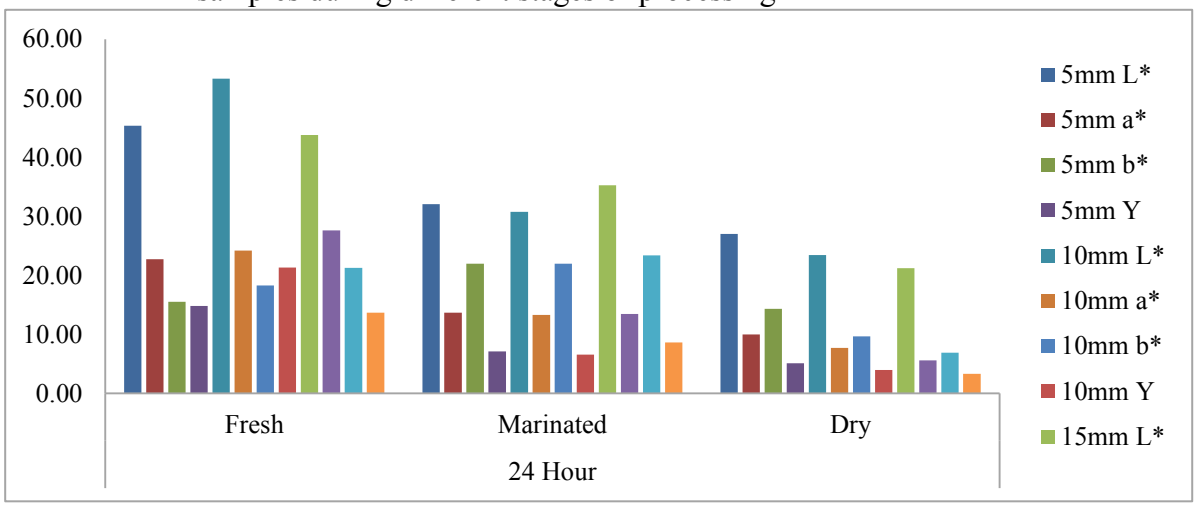


Figure 7.43 Changes in colour attributes of 24-hour marinated HWL infrared dried biltong samples during different stages of processing

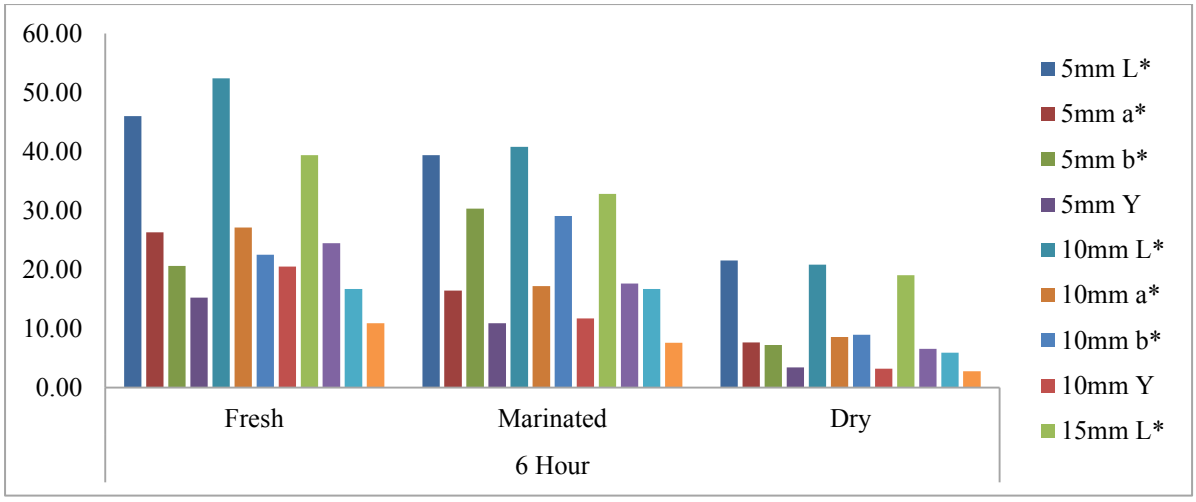


Figure 7.44 Changes in colour attributes of 6-hour marinated LWL infrared dried biltong samples during different stages of processing

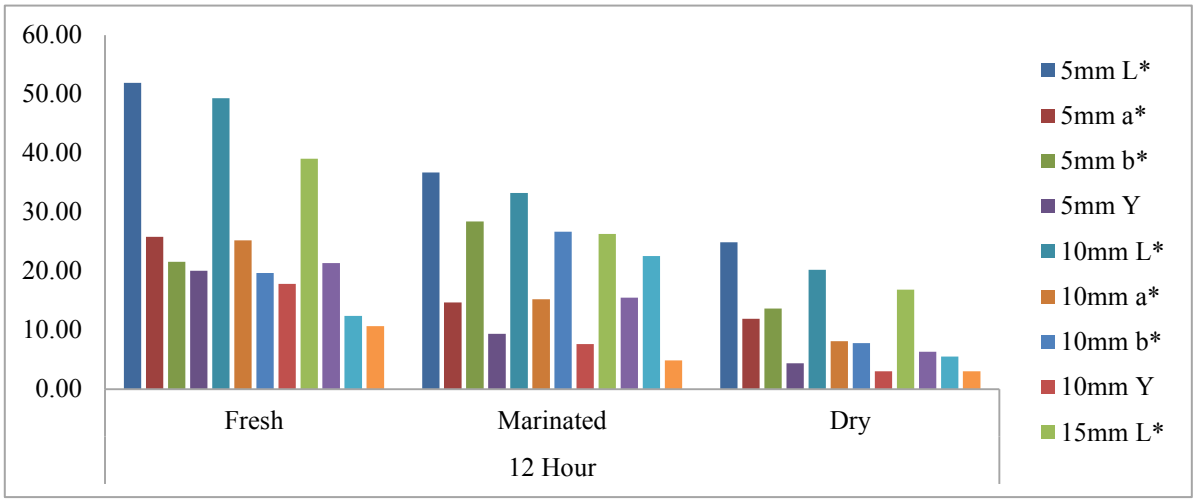


Figure 7.45 Changes in colour attributes of 12-hour marinated LWL infrared dried biltong samples during different stages of processing

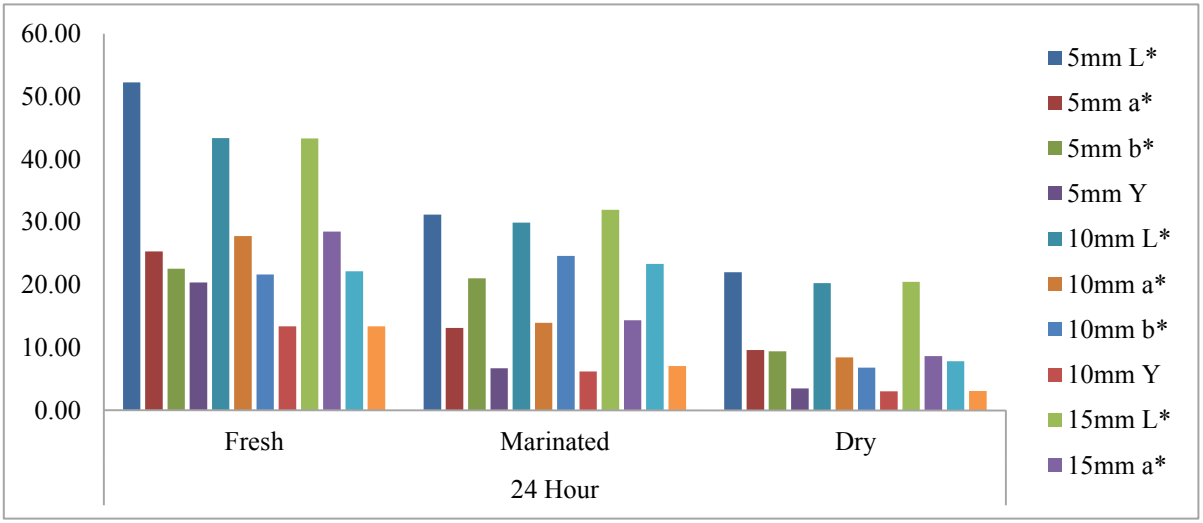


Figure 7.46 Changes in colour attributes of 12-hour marinated LWL infrared dried biltong samples during different stages of processing

## APPENDIX G

Table 7.6 Peak puncture force ANOVA table

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Dryer | 12211.679 | 2 | 6105.839 | 24.182 | 0.000** |
| Marination | 2686.933 | 2 | 1343.466 | 5.321 | 0.015** |
| Thickness | 3178.755 | 2 | 1589.377 | 5.685 | 0.012** |
| Dryer * Marination | 1628.229 | 4 | 407.057 | 1.612 | 0.214 |
| Dryer * Thickness | 649.138 | 4 | 162.284 | 0.580 | 0.681 |
| Thickness * Marination | 408.057 | 4 | 102.014 | 0.124 | 0.972 |
| Dryer * Marination* Thickness | 6273.745 | 8 | 784.218 | 0.954 | 0.500 |
| Error | 14797.916 | 18 | 822.106 | | |
| Total | 85821.264 | 27 | | | |
| Corrected Total | 21071.661 | 26 | | | |

Table 7.7 Texture profile analysis (TPA) ANOVA table for hardness

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Dryer | 632.422 | 2 | 316.211 | 6.747 | 0.007** |
| Marination | 292.371 | 2 | 146.186 | 3.119 | 0.069 |
| Thickness | 717.823 | 2 | 358.911 | 17.385 | 0.000** |
| Dryer * Marination | 56.444 | 4 | 14.111 | 0.301 | 0.873 |
| Dryer * Thickness | 103.039 | 4 | 25.760 | 1.248 | 0.326 |
| Thickness * Marination | 2.505 | 4 | 0.626 | 0.014 | 1.000 |
| Dryer * Marination* Thickness | 1012.699 | 8 | 126.587 | 2.805 | 0.33 |
| Error | 812.194 | 18 | 45.122 | | |
| Total | 8075.748 | 27 | | | |
| Corrected Total | 1824.893 | 26 | | | |

Table 7.8 Texture profile analysis (TPA) ANOVA table for cohesiveness

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Dryer | 0.127 | 2 | 0.064 | 11.829 | 0.001** |
| Marination | 0.008 | 2 | 0.004 | 0.751 | 0.486 |
| Thickness | 0.080 | 2 | 0.040 | 16.780 | 0.000** |
| Dryer * Marination | 0.024 | 4 | 0.006 | 1.118 | 0.379 |
| Dryer * Thickness | 0.007 | 4 | 0.002 | 0.692 | 0.607 |
| Thickness * Marination | 0.002 | 4 | 0.000 | 0.041 | 0.997 |
| Dryer * Marination* Thickness | 0.089[a] | 8 | 0.011 | 1.203 | 0.351 |
| Error | 0.167 | 18 | 0.009 | | |
| Total | 5.998 | 27 | | | |
| Corrected Total | 0.257 | 26 | | | |

Table 7.9 Texture profile analysis (TPA) ANOVA table for gumminess

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Dryer | 255.340 | 2 | 127.670 | 15.899 | 0.000** |
| Marination | 41.419 | 2 | 20.709 | 2.579 | 0.104 |
| Thickness | 116.999 | 2 | 58.499 | 19.820 | 0.000** |
| Dryer * Marination | 10.034 | 4 | 2.508 | 0.312 | 0.866 |
| Dryer * Thickness | 25.866 | 4 | 6.467 | 2.191 | 0.111 |
| Thickness * Marination | 0.851 | 4 | 0.213 | 0.013 | 1.000 |
| Dryer * Marination* Thickness | 159.269 | 8 | 19.909 | 1.227 | 0.339 |
| Error | 292.065 | 18 | 16.226 | | |
| Total | 1803.048 | 27 | | | |
| Corrected Total | 451.334 | 26 | | | |

** Significant at p=0.05

## APPENDIX H

Table 7.10 Shrinkage coefficient ANOVA table

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Dryer | 233.268 | 2 | 116.634 | 4.556 | 0.025** |
| Marination | 309.926 | 2 | 154.963 | 6.054 | 0.010** |
| Thickness | 410.893 | 2 | 205.447 | 6.981 | 0.006** |
| Dryer * Marination | 190.493 | 4 | 47.623 | 1.860 | 0.161 |
| Dryer * Thickness | 20.571 | 4 | 5.143 | 0.175 | 0.948 |
| Thickness * Marination | 8.444 | 4 | 2.111 | 0.082 | 0.987 |
| Dryer * Marination* Thickness | 733.687 | 8 | 91.711 | 3.583 | 0.120 |
| Error | 465.188 | 18 | 25.844 | | |
| Total | 111183.116 | 27 | | | |
| Corrected Total | 1194.451 | 26 | | | |

** Significant at p=0.05

## APPENDIX I

Table 7.11 Rehydration characteristics ANOVA table

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Dryer | 0.272 | 2 | 0.136 | 0.030 | 0.970 |
| Marination | 7.287 | 2 | 3.643 | 0.810 | 0.461 |
| Thickness | 65.922 | 2 | 32.961 | 19.522 | 0.000** |
| Dryer * Marination | 10.952 | 4 | 2.738 | 0.608 | 0.662 |
| Dryer * Thickness | 2.921 | 4 | 0.730 | 0.432 | 0.783 |
| Thickness * Marination | 2.642 | 4 | .661 | .503 | 0.734 |
| Dryer * Marination* Thickness | 18.511[a] | 8 | 2.314 | .514 | 0.830 |
| Error | 23.656 | 18 | 1.314 | | |
| Total | 1473.958 | 27 | | | |
| Corrected Total | 99.507 | 26 | | | |

** Significant at p=0.05

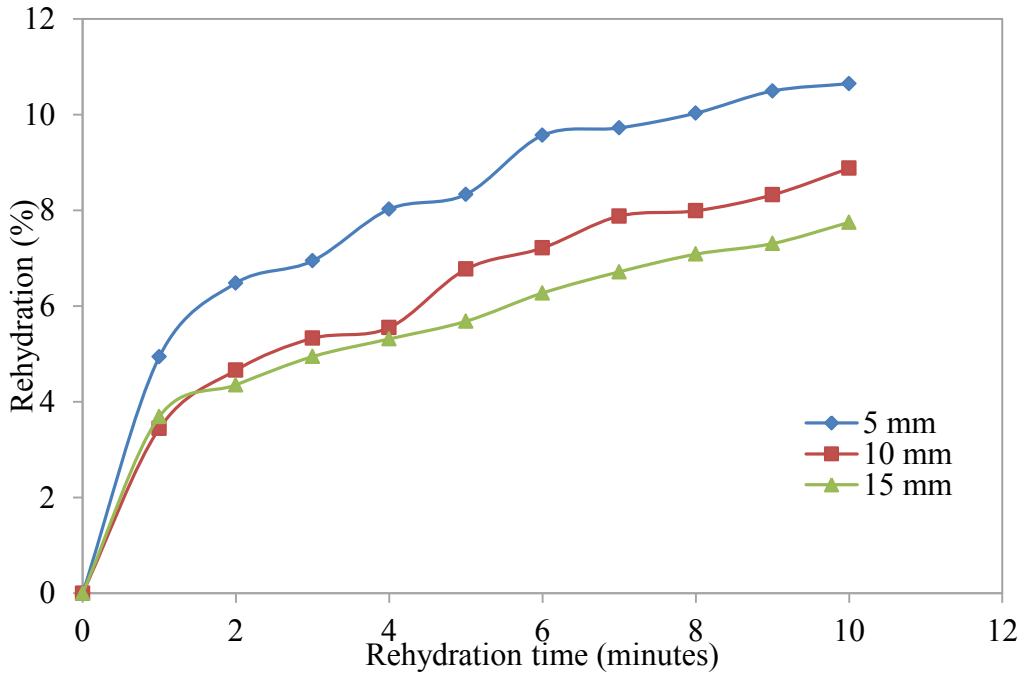


Figure 7.47 Rehydration characteristics for the 12-hour marinated biltong products dried under the convective air dryer

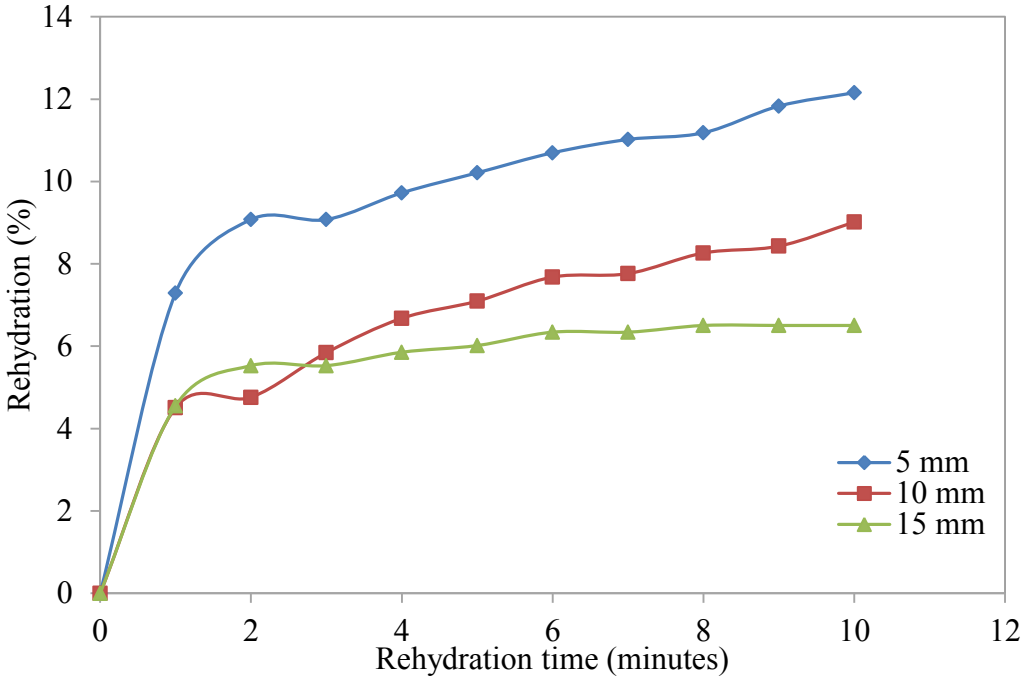


Figure 7.48 Rehydration characteristics for the 24-hour marinated biltong products dried under the convective air dryer

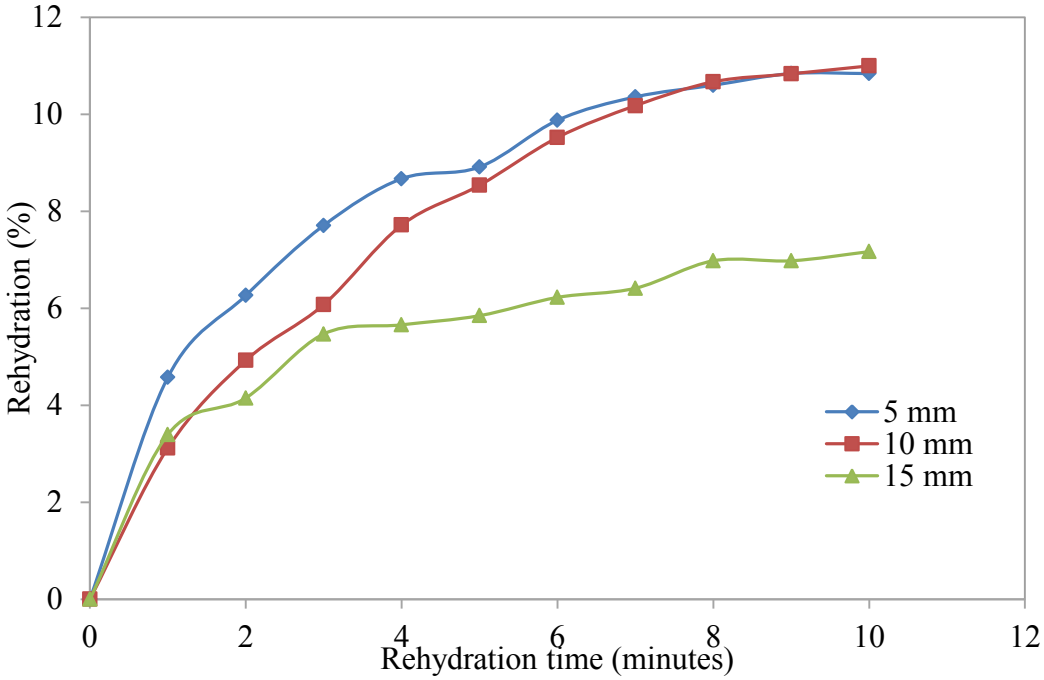


Figure 7.49 Rehydration characteristics for the 12-hour marinated biltong products dried under the HWL infrared heater

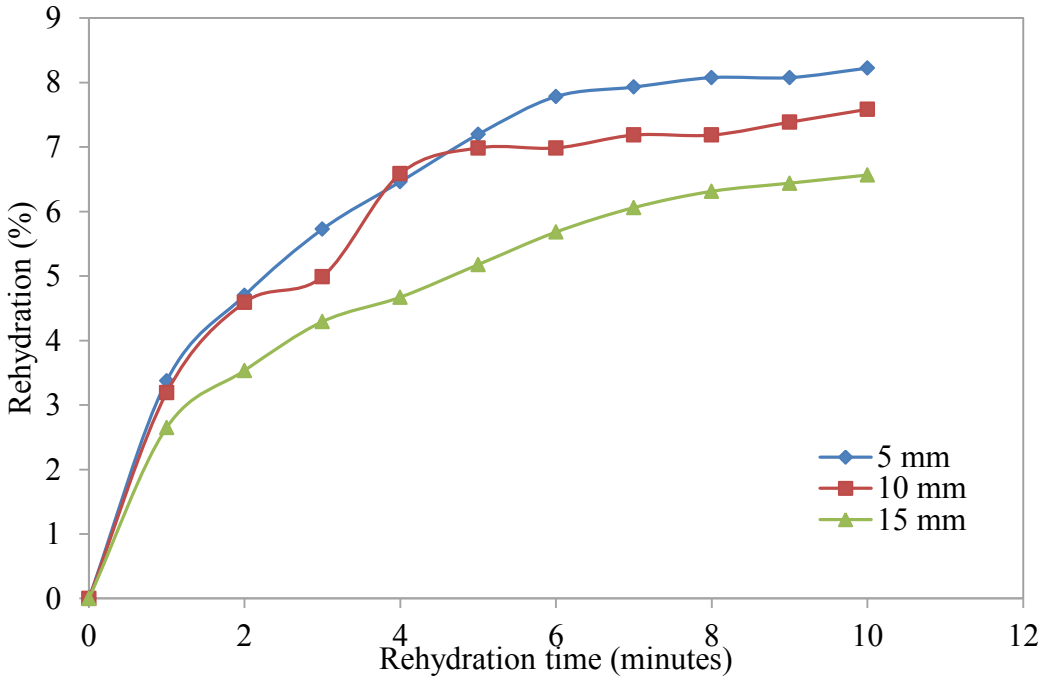


Figure 7.50 Rehydration characteristics for the 24-hour marinated biltong products dried under the HWL infrared heater

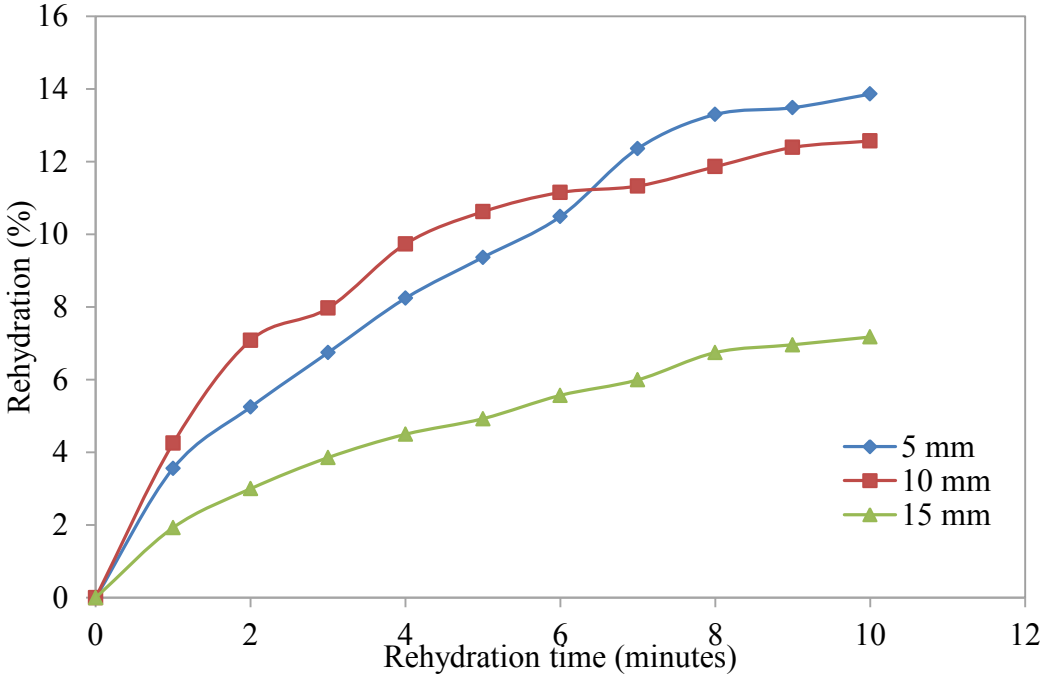


Figure 7.51 Rehydration characteristics for the 6-hour marinated biltong products dried under the LWL infrared heater

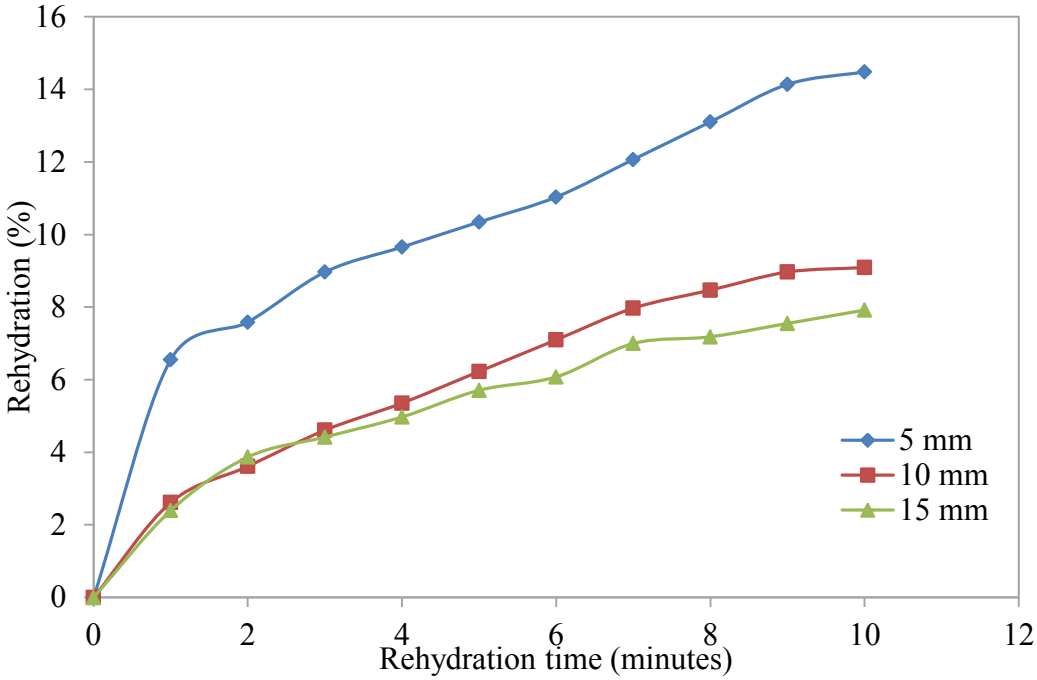


Figure 7.52 Rehydration characteristics for the 24-hour marinated biltong products dried under the LWL infrared heater

**APPENDIX J**

Table 7.13 Ingredients of the most probable number (MPN) culture broth and decimal dilution medium

| Product | Ingredients/litre of distilled water | quantity | PH |
|---|---|---|---|
| MPN Standard 1 medium (MPN culture broth) | Peptone | 15 g | 7.5 |
| | Yeast extract | 3 g | |
| | NaCl | 6 g | |
| | Glucose | 1 g | |
| Decimal dilution medium | NaCl | 8.5 g | 7.0 |

**APPENDIX K**

Table 7.12 The Springiness, resilience and chewiness of biltong samples from texture profile analysis curves.

| Drying system | Sample pre-treatments | | TPA values | | |
|---|---|---|---|---|---|
| | Marinating time (hours) | Thickness (mm) | Springiness | Resilience | Chewiness (kgF) |
| Convective air dryer | 6 | 5 | 0.98±0.01 | 0.50±0.06 | 3.26±1.23 |
| | | 10 | 0.96±0.05 | 0.30±0.07 | 3.95±1.43 |
| | | 15 | 0.97±0.06 | 0.22±0.01 | 9.08±1.42 |
| | 12 | 5 | 0.95±0.02 | 0.27±0.03 | 4.32±1.36 |
| | | 10 | 0.93±0.01 | 0.23±0.02 | 4.38±1.12 |
| | | 15 | 0.89±0.03 | 0.20±0.01 | 9.11±1.53 |
| | 24 | 5 | 0.86±0.01 | 0.41±0.01 | 6.44±0.98 |
| | | 10 | 0.87±0.03 | 0.26±0.02 | 6.89±1.69 |
| | | 15 | 0.85±0.02 | 0.25±0.01 | 10.98±1.58 |
| HWL Infrared heater | 6 | 5 | 0.96±0.04 | 0.36±0.01 | 5.92±1.70 |
| | | 10 | 0.94±0.04 | 0.24±0.05 | 6.41±1.98 |
| | | 15 | 0.91±0.02 | 0.22±0.02 | 11.55±1.25 |
| | 12 | 5 | 0.90±0.04 | 0.42±0.04 | 7.62±1.61 |
| | | 10 | 0.88±0.03 | 0.38±0.09 | 8.50±1.29 |
| | | 15 | 0.85±0.02 | 0.28±0.04 | 12.28±1.55 |
| | 24 | 5 | 0.84±0.05 | 0.48±0.03 | 8.99±1.19 |
| | | 10 | 0.82±0.03 | 0.31±0.01 | 8.79±1.36 |
| | | 15 | 0.81±0.02 | 0.29±0.02 | 13.7±1.84 |
| LWL Infrared heater | 6 | 5 | 0.92±0.04 | 0.25±0.03 | 1.29±1.46 |
| | | 10 | 0.89±0.02 | 0.19±0.03 | 2.06±1.01 |
| | | 15 | 0.86±0.04 | 0.17±0.02 | 3.34±1.96 |
| | 12 | 5 | 0.85±0.02 | 0.21±0.05 | 2.10±1.39 |
| | | 10 | 0.83±0.02 | 0.20±0.04 | 2.74±1.75 |
| | | 15 | 0.81±0.02 | 0.14±0.01 | 3.44±1.44 |
| | 24 | 5 | 0.79±0.03 | 0.28±0.05 | 2.33±1.67 |
| | | 10 | 0.78±0.01 | 0.21±0.02 | 3.06±1.84 |
| | | 15 | 0.76±0.04 | 0.19±0.01 | 3.35±1.22 |

**APPENDIX L**

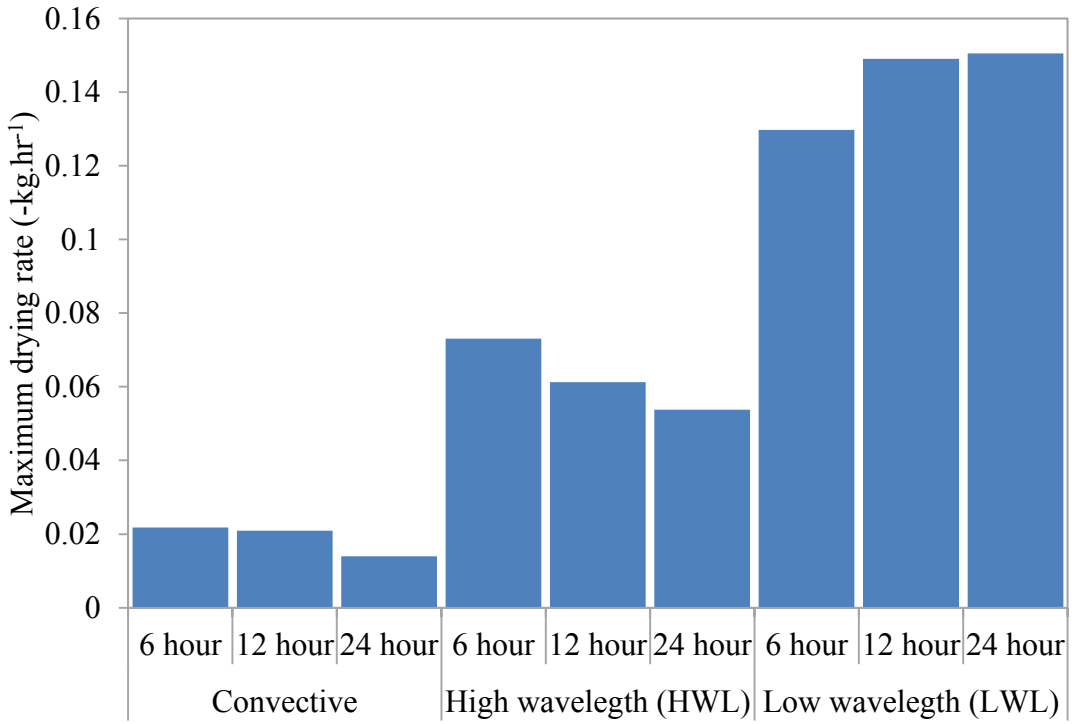


Figure 7.53 Variation of the maximum drying rate with the marinating duration across the three drying systems

## APPENDIX M

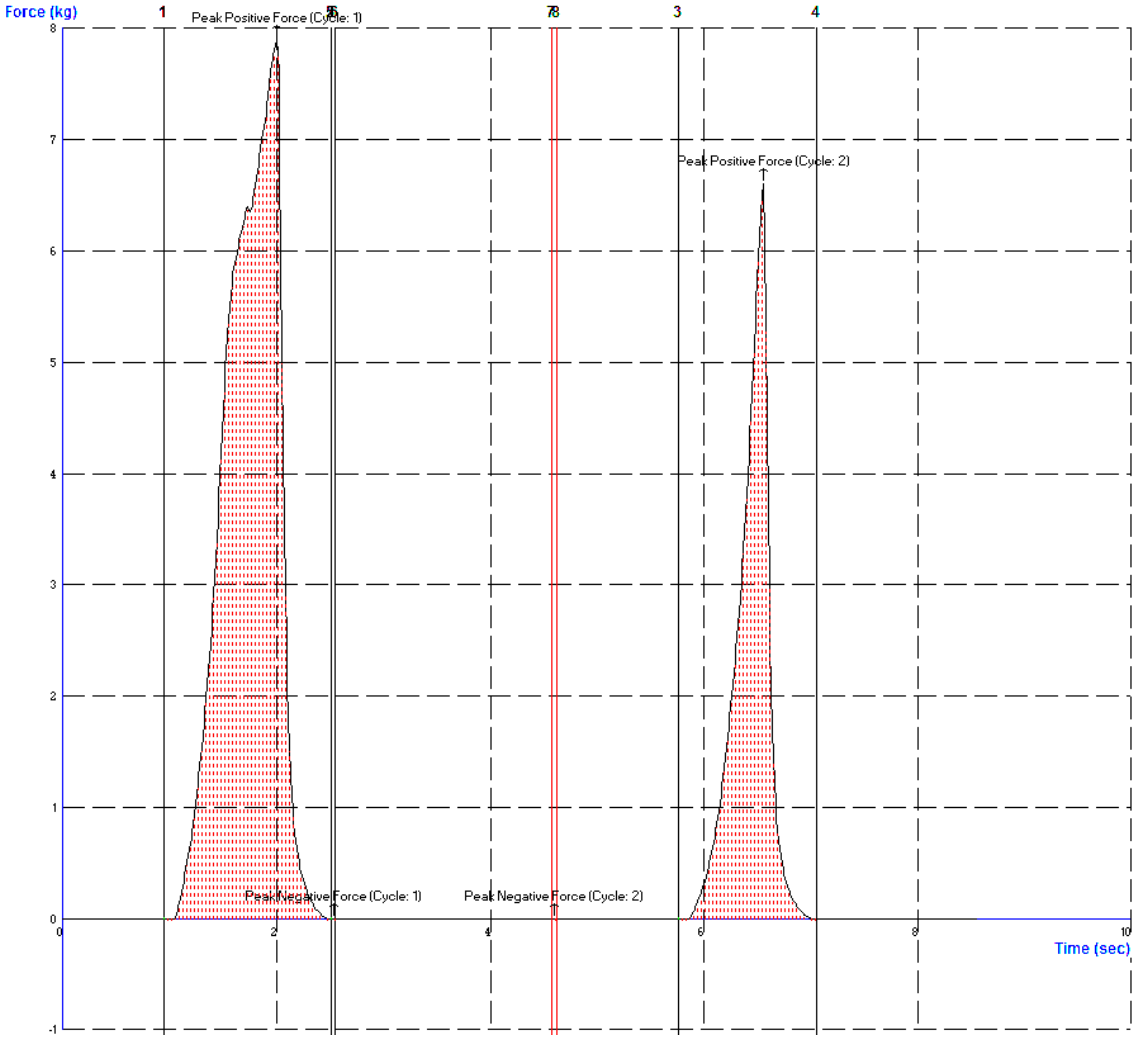


Figure 7.54 A Typical TPA graph of biltong products: TPA plot of 15 mm thick low wavelength infrared dried sample