COMBINED MICROWAVE - CONVECTION DRYING AND TEXTURAL CHARACTERISTICS OF BEEF JERKY

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ABSTRACT

Beef jerky is a dried meat snack which is rich in protein but of low calorific value. This ready-to-eat meat snack is in high demand among hikers, bikers and travelers due to its compact nature and nutritional value. The current processing methods such as smoke house and home dehydrators take 6-10 h. Increasing market for this shelf-stable meat product increases the need for alternate efficient processing method. Also, this meat snack market depends on its textural characteristics which denote the consumer acceptability. In this research, three different methods of drying beef jerky were examined.

Influences of pH and salt on different characteristics of beef jerky were investigated using combined microwave-convection drying. Also, the effects of relative humidity and airflow rates in forced air thin layer drying on jerky processing were studied. Samples of beef jerky dried using a combined microwave-convection drier and thin layer drying unit were compared with samples dried in a smoke house.

The results obtained showed that pH and salt content had a significant influence on drying, physical and textural characteristics of jerky. It was found that samples with low pH (5.15) and high salt content (3.28% (w/w)) dried faster than samples with high pH and low salt content due to their high drying rates. These samples had shown high shrinkage and weight loss compared to samples with pH 5.65 and 1.28% (w/w) salt content. Analysis of the textural characteristics such as tensile force, puncture force and texture profile showed that the samples with high pH and low salt content were comparably softer than the rest of the samples. Results of the effect of relative humidity and airflow rate in forced air thin layer drying on jerky processing showed that relative humidity and airflow rate influenced the drying, physical, chemical and textural characteristics of beef jerky. Combination of low relative humidity and high airflow rate showed desirable drying characteristics. However, samples dried at this combination showed high shrinkage and weight loss. The hardness of the beef jerky increased with increase in airflow rate and reduction in relative humidity.

A comparison of the drying methods revealed that different drying methods produced different desirable properties. Combined microwave-convection drying was found to be efficient and very rapid (8.25 min). The low shrinkage and weight losses along with high drying rate obtained using this method would pave a way to fast and efficient processing. The color and textural characteristics were different from those of samples dried in a smoke house. Surprisingly, combined microwave-convection drying method produced softer beef jerky than thin layer and smokehouse methods. However, the commercially available jerky is tougher than the one dried using combined microwave-convection drying. The samples dried in a thin layer drier had comparable color and textural characteristics with samples dried in a smoke-house. Also, forced-air thin layer drying method reduced drying time of beef jerky from 7 to 3 h. The forced air thin layer drier has the potential to produce beef jerky with similar color and textural characteristics to commercially available smoke house dried samples.

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DEDICATED TO

MY BELOVED FAMILY

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NOMENCLATURE

ε^r	Complex permittivity
ε'	Dielectric constant
ε''	Dielectric loss factor
MR	Moisture ratio
MC (wb)	Percentage wet-basis moisture content (Kg of water per kg of material)
MC (db)	Decimal dry-basis moisture content (kg of water per kg of dry matter)
K	Drying constant (min^{-1} or h^{-1})
n	Exponential part of drying constant
L^*	Lightness value
a^*	Redness/greenness value
b^*	Yellowness/blueness value
ΔE	Color index
a_w	Water activity
RH	Relative humidity (%)
pKa	Acid dissociation constant
H^+	Hydrogen ion
pH	Potential of hydration
SD	Standard deviation
CV	Coefficient of Variation
CIE	A color standard
j	Complex operator $\sqrt{(-1)}$

CHAPTER I

INTRODUCTION

1.1. Overview

The North American meat snack industry is comprised of jerky, meat sticks, and other meat and cheese snacks. Beef is one of the main ingredients in majority of the meat snacks. Over 80% of the meat snack market is beef based. Since 1997, the market for meat snacks has grown 14% (Bosse and Boland, 2008). Mintel International Inc. (2007) reported that the market for meat snack in the United States increased from 2001 to 2006 and it reached $3.2 billions in 2006. The reported growth in the market of meat snacks is due to their low carbohydrate, fat content and diverse flavor selection (Bosse and Boland, 2008). He also reported that jerky has an estimated sale of 44% among meat snacks. Jerky is a well known meat snack which is rich in protein content.

The name jerky was derived from the Spanish word 'Charque', meaning dried meat. Jerky is made by slicing the meat into strips and drying (whole meat jerky) or by grinding the meat and drying (restructured jerky). The processing of jerky involves salting and drying to improve its shelf life. The high protein content, low fat content and low calorific value of this dried meat product made it popular in the consumer market. It is liked by a wide range of consumer groups such as hikers, bikers and travelers because of its compact nature and nutrients.

Due to recent food poisoning outbreaks, the processing procedures for jerky has been regularized by the United States Department of Agriculture (USDA). The present recommendation is that a jerky having moisture-to-protein ratio of 0.75:1 and water activity of not more than 0.85, is safe. These values inhibit the growth of pathogens and assure product safety. Also, it is recommended that the product temperature should reach 71°C during processing (USDA, 2003).

Although jerky is in high demand in the market, no effort has been taken to optimize its process conditions. Commonly reported methods in practice for jerky processing include drying in a smoke house and home dehydration. The American Association of Meat Processors (2004) reported that this traditional method takes 6-10 h at 60ºC. Reducing the processing time would certainly lead to the reduction in the product cost and increase efficiency. It is essential to have a good understanding of the processing behavior in order to optimize the process.

It is reported for several other food products that it is 75% more energy efficient to utilize electromagnetic energy for the drying process (Quenzer and Burns, 1981). In the meat industry, microwaves are currently employed to pasteurize poultry meat. There are advantages in using microwave energy over conventional types in terms of energy savings, reduced processing time, enhanced quality attributes and cost effectiveness. It was reported by Cunningham (1980) that meat treated with microwave energy for less than 20 s showed no drastic change in appearance. The application of new innovative, energy efficient technology has not been experimented for jerky processing yet. To the best of the author's knowledge, there is no single study reported on systematic drying of beef jerky or dried beef products.

In this present study, an attempt was made to explore different drying methods for jerky processing. Also, the effects of different product formulations on its processing behavior were investigated.

1.2. Objectives

The objectives of this study were:

1. To investigate the effect of pH and salt content in a combined microwave-convection drying of beef jerky.
2. To explore the effect of air-flow rate and relative humidity in forced air thin layer drying environment of beef jerky.
3. To compare beef jerky processing under combination of microwave and convection, thin layer cross- flow and smoke-house drying methods.

CHAPTER II

LITERATURE REVIEW

In this chapter, the current jerky processing methods and product quality parameters are reviewed briefly.

2.1. Beef Jerky

2.1.1. History of jerky

Jerky is a nutritious, dense and shelf-stable form of preserved meat which is traditionally prepared by slicing the whole meat into long, thin strips which are then dried. The word "jerky" was derived from the Spanish word "charque" which means dried meat (AAMP, 2004). It was found that jerky has been a part of the human diet since ancient Egypt (FSIS, 2000). It was used as a major staple food in emergency rations and for travellers where fresh meat was not available. Pemmicans have been prepared by combining the dried meat with dried fruits or animal fat by the American Indians. It is reported in the literature that pemmican was the food that enabled Alexander Mackenzie to cross the North American continent in 1793 (AAMP, 2004).

Jerky's high protein content and popularity have increased the dried meat snack market to $250 million in 2004 (AAMP, 2004). Branded jerky costs around $35 per pound (AAMP, 2004). Jerky is prepared by drying thin strips of lean meat to about one-half of its original weight. It can be made from any form of meat; sliced or ground meat. The former one is called whole muscle jerky, while latter is called the re-structured or formed jerky.

2.1.2. Food safety concerns of beef jerky

Several outbreaks of microbial infections called for a revision of food safety measures and processing procedures for jerky. Several studies have been conducted since the past two decades to control pathogens such as *Escherichia coli* O157:H7, *Listeria monocytogenes* and Salmonella (Yoon et al., 2005; Calicioglu et al., 2002; 2003). It was reported that the product needs to be heated prior to drying and addition of sodium nitrite to the formulation improved the rate of destruction of pathogenic microorganisms (AAMP, 2004). The United State Department of Agriculture strongly recommends that the meat should be heated to 71°C before drying (USDA, 2003).

Eidson et al. (2000) reported six Salmonella and two *Staphylococcus aureus* food-borne illness outbreaks in beef jerky in New Mexico between 1966 and 1995. Food-borne illness outbreaks associated with beef jerky consumption due to *Escherichia coli* O157:H7 in venison jerky (Keene et al., 1997) and Salmonella (USDA/FSIS, 2003) have also been reported. Another study carried out by Levine et al. (2001) concluded that between 1990 and 1999 there were 0.31% and 0.52% of cumulative occurrence of *Salmonella* and *Listeria monocytogenes* in the jerky produced by federally inspected plants. Therefore, there is a strong need to evaluate the present drying and processing procedures to make safer jerky (Yoon et al., 2005; Archuleta, 2004).

In the past ten years, several researches have been carried out to rectify the above mentioned issues and assure food safety. Harrisons and Ruth Ann Rose (1998) reported that ground beef jerky prepared with curing mix salt and sodium nitrate showed greater percentage of bacterial destruction than the one prepared without curing mix. Another study done by Quixton (1997) concluded that high acid content achieved by varying the pH of the jerky formulation with vegetables and meat proteins have resulted in better shelf stability than the normal one.

After an extensive review of the microbial control in intermediate moisture foods, the United States Department of Agriculture (USDA) revised the standards for this shelf staple food product, which is found in Food Standards and Labelling Policy Book (USDA, 2003). The new standards recommend having at least moisture to protein ratio of ≤ 0.75:1 and water activity of not more than 0.85 to ensure product safety. Indeed, any meat product with a water activity (a_w)

of less than 0.85 is commonly considered as ‘shelf stable’ as this value indicates the measure for controlling *Staphylococcus aureus*. However, the Food Safety and Inspection Service-Meat and Poultry Compliance Guidelines (2004) suggested that critical water activity limit for jerky, which is in contact with air, be ≤ 0.70, as mold growth is arrested at this water activity level. Different biological hazards with their controls are shown in Table 2.1 (AAMP, 2004).

Table 2.1. Biological hazards and controls (adapted from AAMP (2004)).

Microbial Hazard	Minimum a_w	Temperature (°C) ($\log_{10}$ reduction)	Minimum pH
Campylobacter	NA	71.2°C (Meat) 82.3°C (Poultry)	4.0
Clostridium perfringens	0.93	60°C	5.0
E. coli O157:H7	0.95	70°C (for 2 mins)	4.4 (O157:H7 is reported to be acid resistant surviving at pH values below 4.4)
Listeria monocytogenes	0.92	70°C (for 2 mins) 10^7 log reduction	4.39
Salmonella	0.94	70°C (instant) 10^7 log reduction	3.8
Staphylococcus aureus	0.85	60°C	4.0

2.1.3. Product development

Increasing demand for jerky among women and children has accelerated research in new product development. Studies have been conducted to look for an alternative non-meat source for protein. Ray (1996) tried 2:3 ratio of potato flour with meat to make jerky and reported that this product had a significant nutritional advantage due to its high carbohydrate and protein content. Another attempt by Quixton et al. (1997) to prepare softer jerky by incorporating 50% (w/w) dehydrated vegetables with meat failed in sensory evaluation, due its unappealing appearance.

2.2. Meat Preservation

Meat, being one of the essential sources of protein and a wide variety of other nutrients, has been consumed by humans as a major food since the prehistoric era. However, as the consumption rate and the production of meat grow invariably with time, the nature of the product requires that it be preserved for future use. The high water content of meat makes it extremely perishable. Food preservation is employed to prevent undesirable changes in the nutritive value and sensory quality of food by controlling the growth of micro-organisms and reducing the physical, chemical and microbiological changes, which in turn improve the economic value of the product. Military and exploratory efforts have always had a strong influence on preservation technology because they have depended on a reliable and continuous food supply for success. Improved transportation allowed better distribution. A variety of methods are used in combination to produce the greatest preservation while keeping quality high. The effectiveness of a preservation method is somewhat like a balancing act. It must be used to a degree that achieves the preservation desired, yet does not adversely alter the appearance or quality of the food (Cassens, 1994). There have been enormous advancements in meat preservation with the result of making available high quality and safe meat and meat products.

Although there are a variety of physical, chemical and biological means of preserving meat, a few major preservation methods are discussed in the following subsections.

2.2.1. Drying and dehydration

In general, drying is the lowering of water activity of a perishable product accomplished by removing water, where micro-organisms would not be able to get sufficient water for survival. It is a complex operation involving transient heat and mass transfer along with physical transformations such as shrinkage, puffing, crystallization or glass transition and chemical or biochemical reactions which cause changes in color, texture, odor etc. (Mujumdar and Devahastin, 2000). On the whole, it affects the final quality of the end product. So, the selection criteria for drying methods relies on the type of the product to be dried, desired final product quality, the product’s susceptibility to heat and the operation cost (Cohen and Yang, 1995).

Drying is the oldest method of food preservation, as it is known that drying and salting were practiced in the Nile valley by early societies (Cassens, 1994). The most desirable advantages of drying are the low storage space, low transportation cost, simple operative method and low cost. It was reported by Humphrey (2002) that the protein content of dried meat is higher than the fresh one.

Drying at a very high temperature results in an improperly dried product due to the case hardening phenomenon of food materials. Temperature and relative humidity of the air affect the equilibrium moisture content and the composition of the surface. Moisture transfer from the surface of the meat product to the surroundings depends on its water content and composition. Nevertheless, temperature and relative humidity of the environment and characteristics of boundary layer are also important (Simal et al., 2003).

2.2.2. Salting

As salt is an effective inhibitor of microorganisms, salting of foods has been used as a preservation method for a long time. It is known that salt binds with water molecules and thus acts as a dehydrating agent in foods. A high level of salinity may impair the conditions under which pathogens can survive. Salt that is added during processing has an influence in changing the ability of lean meat to retain water (Ranken, 2000). Water holding capacity can be enhanced by the addition of the salts of strong acids such as sodium chloride (Gerrard, 1935). The more strong ions are bound by the protein, the stronger will be the hydrating effect (Hamm, 1957). At high pressures, water behaves similar to solutions with increasing salt content in that the water activity apparently decreases with increased pressure (Koop et al., 2000). Salting reduces the water activity of the food product (Henning, 2004). Salt interacts with water through ionic and dipolar bonds, and thus reduces the water available for the growth of microorganisms.

2.2.3. pH

Compared to other means of preservation, manipulation of pH is less complicated in terms of expense and equipment. pH is the measure of the activity of hydrogen ions (H^+). It is one of the main factors in controlling the microbial stability of food products that are acidified or fermented. The minimum pH required to destroy the major hazardous micro-organisms are tabulated in Table 2.1. A study by Unklesbay et al. (1999) showed a significant effect of pH in beef jerky samples cooked in a smoke house, where the pH of the samples was altered by using citric acid. At a low pH, the myofibrillar proteins denature, allowing the water molecules to evaporate freely. At the isoelectric point of meat protein, the water holding capacity is minimum (Cassens, 1994). According to Cassens (1994), at the pH range of 5.1 to 5.0, the positive and negative ions were almost equal resulting in the most compact physical structure in which water molecules can reside or be immobilized.

2.3. Drying Methods

This section deals with different drying methods commonly used in the agri-food industry. There are varieties of different drying methods available to develop new products.

2.3.1. Thin-layer drying

In this method of drying, sensible heat of heated air is transferred to the wet products by convection. Heated air is ventilated through the thin layer of wet material and carries with it the water vapor evaporated from the material. Airflow rate influences convective mass transport (Hamdy and Barre, 1969). A number of researchers have chosen to neglect the effect of air-flow rates in the analysis of thin layer drying data, citing the conclusion of Henderson and Pabis (1962) that resistance to moisture at the surface is negligible compared to the internal resistance. The humidity of drying air has a significant impact on the final or equilibrium moisture content that is achieved as a result of drying. In addition, the driving force for convective transport at the surface of the drying material depends on the difference between the partial pressure of water vapor at the surface and that of the drying air (Fortes and Okos, 1981). The effect of temperature on drying of different agricultural materials is well documented in the literature (Henderson and Pabis, 1961). Most of the material properties that are relevant to drying, for example, mass diffusivity, thermal conductivity and latent heat of evaporation, are temperature dependent (Singh et al., 1972). There are several works done to evaluate the drying model for different plant based products in a thin layer dryer. Researchers have developed numerous thin layer models for various agricultural products. Generally these models are based on thin layer data characterizing the change in drying constant and moisture diffusivity under constant drying conditions (Babalis et al., 2005). There is no literature on thin layer cross flow drying or any other drying methods of meat and meat products.

2.3.2. Microwave drying

In conventional drying methods, the heat required to evaporate the moisture has to be transmitted inward through the moist material from the surface. This hurdle is eliminated in dielectric heating, where internal heat generation phenomenon is the source of drying. Dielectric drying is achieved by volumetric heating of the material by electromagnetic energy (Strumillo and Kudra, 1986). Microwave drying uses electromagnetic wave as a form of energy, which interacts with materials, thus generating heat and increasing the drying rate dramatically (Mujumdar et al., 1987). The capacity of a food product to be heated when exposed to microwave radiation depends on its dielectric loss coefficient, which reflects the limit of the material to convert the electromagnetic field to thermal energy (Taher and Farid, 2001).

Microwaves fall between radio and infrared waves having a wavelength of 0.025 to 0.75 microns and a frequency range of 300 MHz to 300 GHz. In North America, the Federal Communications Commission (FCC) has permitted only the following microwave frequencies: 915, 2450 and 5800 MHz. Electromagnetic waves, including microwaves, possess energy in the form of high energy packets known as quantum energy. When the quantum energy exceeds chemical energy, it can break chemical bonds. Approximately 75% less energy is required for microwave heating as compared to conventional methods (Quenzer and Burns, 1981).

Microwaves and radio waves which have long wavelengths, low frequency and low energy do not have enough energy to break chemical bonds (Knutson, 1987). Therefore, they are non-ionizing. The quantum energy in the microwave is responsible for the creation of heat as the microwave oscillates 2450 x 10^6 times per second and the dipole molecules align to the electric field of the microwave at the same rate.

Alternating electric fields stimulate the oscillation of the dipoles of the atoms in water. Heat is generated due to the molecular friction between dipole molecules. Figure 2.1 shows the breakage of water molecular bonds. Breakage in chemical bonds might occur due to this heat generation, but not due to the microwaves directly (Knutson, 1987). The electric field component of microwave is responsible for heating (Meda and Raghavan, 2005). It causes the molecules of dielectric materials to rotate, and produces a rise in temperature due to friction between molecules. It is reported that the magnetic field components do not take part in heating food.

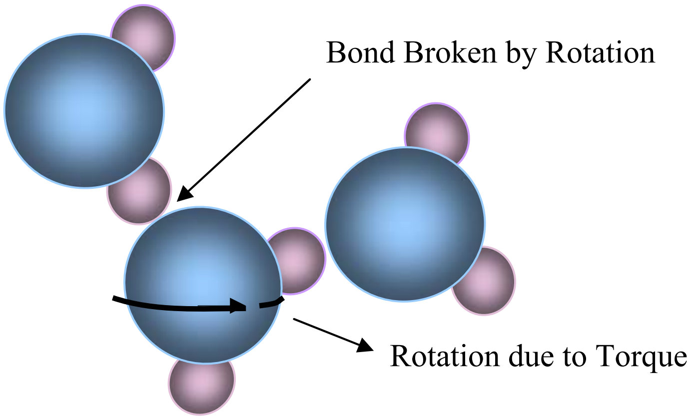

Figure 2.1 Breakage of bonds of water molecules in microwave field

Inside the microwave oven, when incident and reflected microwaves interact, standing wave patterns are formed. The standing wave patterns have maximum and minimum values at certain distances from the reflecting surface. The incident and reflected waves are always in continuous motion (Lorenson, 1990). Inside a microwave oven, there are high possibilities for multiple reflections and hence there are a number of standing wave patterns, leading to non-uniformity in energy distribution.

Several studies have reported that microwaves could be used for surface pasteurisation of meat. Teotia and Miller (1975) reported that 600 and 120 s bursts of microwave energy at 2450 MHz were required to totally destroy *Salmonella senftenberg* on broiler carcasses and turkey drumsticks. Meat treated with microwave energy less than 20 s showed no drastic changes in appearance (Cunningham, 1980). Partial thawing of meat products has been a major use for microwaves in the meat industry (Taher and Farid, 2001). Research on electromagnetic radiation such as near and far infrared, microwave and radio frequency has also been applied to the meat industry. Zhang et al. (2004) studied the effect of radio frequency cooking on the texture, color and sensory properties of meat and it was concluded that the radio frequency heating reduced the pasteurization time nearly 79% compared to steam cooking. Infra-red cooking is of particular interest in the meat sector (Sheridan and Shilton, 1999). Also, they reported that the presence of fat had no effect in mid-infrared radiation and, in the case of far-infrared radiation, a number of mechanisms reduced the cooking time more than with mid-infrared radiation cooking. Ohlsson and Bengtsson (1971) have studied microwave heating in slabs of food and food substitutes and developed a one dimensional heat conduction model. Taher and Farid (2001) reported that the time required to thaw the frozen minced beef using microwave energy was only one-fifth of the time required in conventional method.

2.3.3. Freeze drying

Freeze drying is the process of removing water from a product by sublimation and desorption. Sublimation is the transformation of ice directly into a gaseous form without passing through a liquid phase. Figure 2.2 shows the phase diagram of water. Sublimation occurs when the vapor pressure and the temperature of the ice surface are below the triple point of water (4.58 mmHg, 0°C). Freeze drying was first instituted in the early 1900's as a means for high quality preservation of biological things such as human serum (Irzynic et al., 1995). Freeze dried products have high structural rigidity, high rehydration capacity and low density and they retain raw material properties such as appearance, shape, taste and flavor (Hui et al., 2004).

Ang et al. (1977) have studied the edge effect for cubic beef samples in microwave freeze drying and reported that the pressure had an influence in sample temperature and little effect on drying time. Sagara (2001) studied the transport properties for freeze dried beef and developed a model to predict the permeability of water vapor flow through the dried layer in freeze drying. Ratti (2001) reviewed the hot air and freeze drying by taking into account several important characteristics such as shrinkage, glass transition temperature, process quality interaction, drying kinetics and costs. It was also concluded by Ratti (2001) that freeze drying can be used as the alternative preservation method where food quality is of main concern.

Hui et al. (2004) studied the microwave freeze drying characteristics of raw beef for various levels of electric field strength, vacuum pressure, sample thickness and initial saturation. They concluded that same quality of dried product could be obtained in much shorter time with microwave freeze drying than conventional freeze drying.

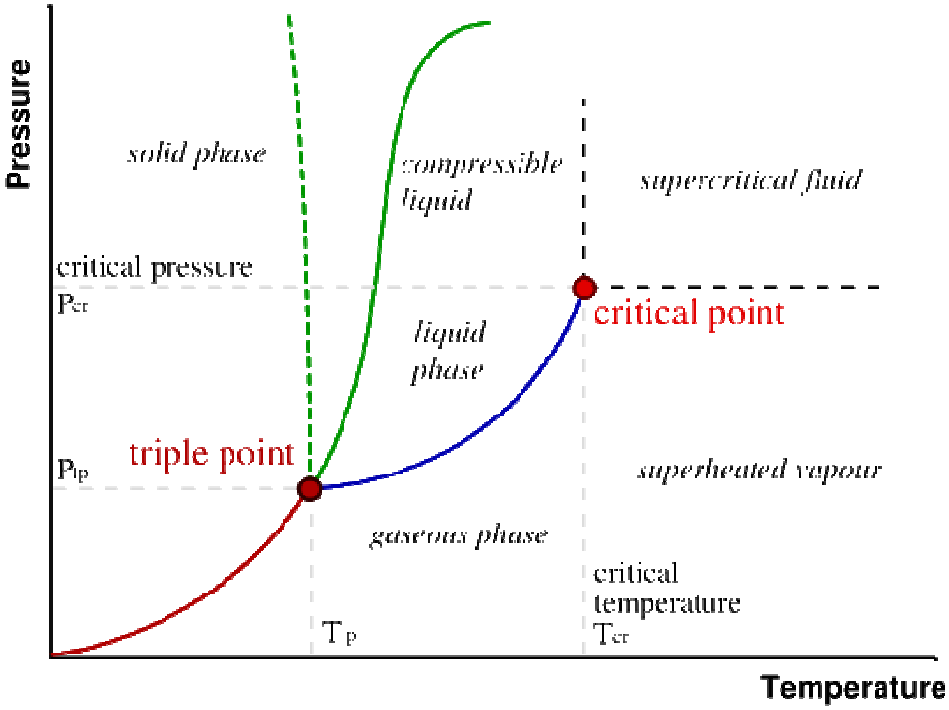

Figure 2.2 Phase diagram of water (adapted from www.wikipedia.org)

Luyet (1962) demonstrated that for freeze dried meat, the rate and extent of rehydration was influenced by the initial freezing rate, which determines the size and location of the corresponding cavities in the freeze dried product. Luyet (1962) also discussed rehydration in terms of two phases: (1) the penetration of water through the cavities and, (2) the absorption of water by the solid tissue surrounding the cavities. It was found that whether the cavities exist within the fibres, as in rapid freezing, or between the fibres, as in slow freezing, water apparently moved more freely through the tissue framework than through the cavities. Air in intermediate size cavities (about 10 μm diameter) that occur in slowly frozen tissue may interfere with rapid rehydration. The air is ultimately dissolved or expelled. In addition to entrapped air, other impediments to rehydration are water repellent surfaces and relatively impermeable membranes. Surface active agents can be added to increase wettability of the surfaces. Luyet (1962) also observed that water absorption into the muscle fibers proceeded faster in the radial direction than longitudinal direction. Even though the cost of production is two to five times higher than conventional drying methods, freeze dried meat is used by the military, campers and explorers, and is also used in some dried food mixes (Ratti, 2001).

2.3.4. Smoke house drying

Smokehouse preservation is almost as old as open air drying. Smoke has the added effect of imparting desirable flavors to the food. Some of the compounds formed during smoking may have bactericidal properties. The composition of the smoke is of major importance for the quality of smoked products (Sebastian et al., 2004). Although not primarily used to reduce the moisture content of the food, the heat associated with the generation of smoke has a drying effect (Cohen and Yang, 1995). This slow cooking technique keeps the final product tender (FSIS, 2003). Dried beef prepared by proper smoking would lose from 25 to 35% of its green weight (Tomhave, 1955).

2.4. Dielectric Properties

Dielectric properties are of primary importance to evaluate the suitability and efficiency of microwave heating. The dielectric properties of usual interest are the dielectric constant (ε'), dielectric loss factor (ε'') and penetration depth (D_p). ε' and ε'' are the real and imaginary parts, respectively, of relative complex permittivity (ε^r). The dielectric properties are often defined by the complex permittivity equation (Nelson, 1973):

$$\varepsilon^r = \varepsilon' - j\varepsilon'' \qquad (2.1)$$

where,

ε^r = Complex permittivity,

ε' = Dielectric Constant (Real part), and

ε'' = Dielectric Loss Factor (Imaginary part)

$j = \sqrt{(-1)}$

Values that can be presented are those of the dielectric constant, ε', and the dielectric loss factor, ε'', respectively, the real and imaginary parts of the complex relative permittivity, $\varepsilon = \varepsilon' - j\,\varepsilon''$ (Nelson, 1973). Values for the loss tangent, $\tan\delta = \varepsilon'' / \varepsilon'$ (where δ is the loss angle of the dielectric) can be calculated from the ε' and ε'' values. The dielectric constant, loss factor, and loss tangent (sometimes called the dissipation factor) are dimensionless quantities. Mudgett et al. (1974) reported that the amount of free moisture in a substance greatly affects its dielectric constant since water has a high dielectric constant, approximately 78 at room temperature.

Lyng et al. (2005) reported the dielectric loss factor of 1.5% and 2.5% salt as 29.19 and 36.37, respectively, at 2540 MHz frequency. The dielectric loss factor of beef alone was reported to be 13.7 (Lyng et al., 2005). When blended with 1.5% (w/w) salt, the dielectric loss factor increased to 24.4 (Lyng et al., 2005). At 2450 MHz frequency, the dielectric loss of the water mixed with 0.5% (w/w) salt was measured as 15.6 and that of distilled water was measured as 10.3. A study done by Rozzi and Singh (2000) on starch solutions containing salt revealed that the microwave heating profile of the samples containing salts versus those without salt were significantly different. Also, Tang (2005) reported the change in the dielectric properties of mashed potato with 0.8 and 1.8% (w/w) salt. He has reported that the dielectric loss factor was increased from 16.3 to 19.4 by the addition of more salt.

2.5. Water Activity

Water activity is defined as the ratio of water vapor pressure measured in the product to the pressure of a saturated water vapor atmosphere at the same temperature. Water activity is also defined as the free water available to microorganisms to grow. Distilled water has a water activity of 1.0. When solutes like sugar or salt are added to the water, the water activity reduces due to water molecule and salt/sugar interactions which lead to a reduction in available water (Henning, 2004). Low moisture content is only an indication of food stability and not a guarantee. The availability of moisture for microbial growth has more impact on product safety than water content. The minimum available water necessary for bacterial growth varies with the type of organism. According to the FAO, the lowest water activity for normal bacteria, yeast, molds and salt tolerant bacteria is 0.91, 0.88, 0.80 and 0.77, respectively. It was reported by the USDA (2001) that toxin production by *Staphylococcus aureus* is inhibited at water activities of 0.92 for anaerobic condition and less than 0.90 for aerobic condition. Figure 2.3 shows the activity of different sources of deterioration at different water activity level. There are only limited details about the relation between water content and water activity (Serra et al., 2005). Reducing the water activity and pH may retard or impede microbial growth. Figure 2.4 gives the relationship between water activity and moisture content for different food groups.

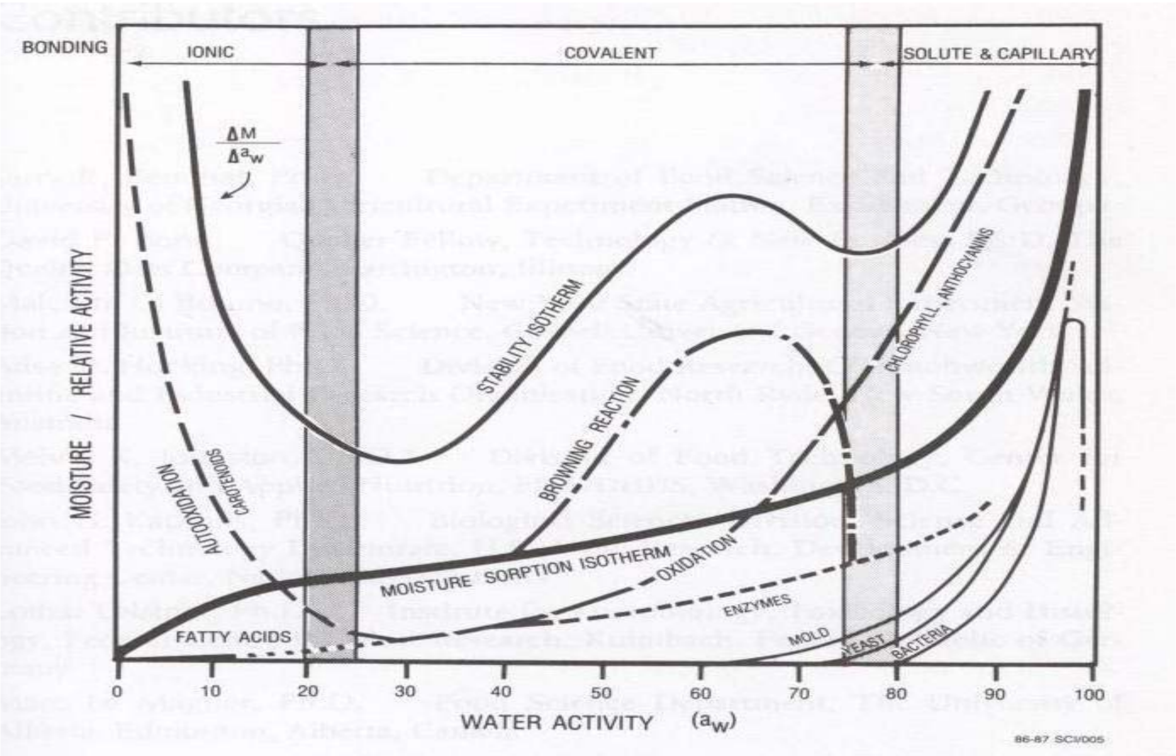

Figure 2.3. Deterioration rates as a function of water activity (Rockland and Beuchat, 1986).

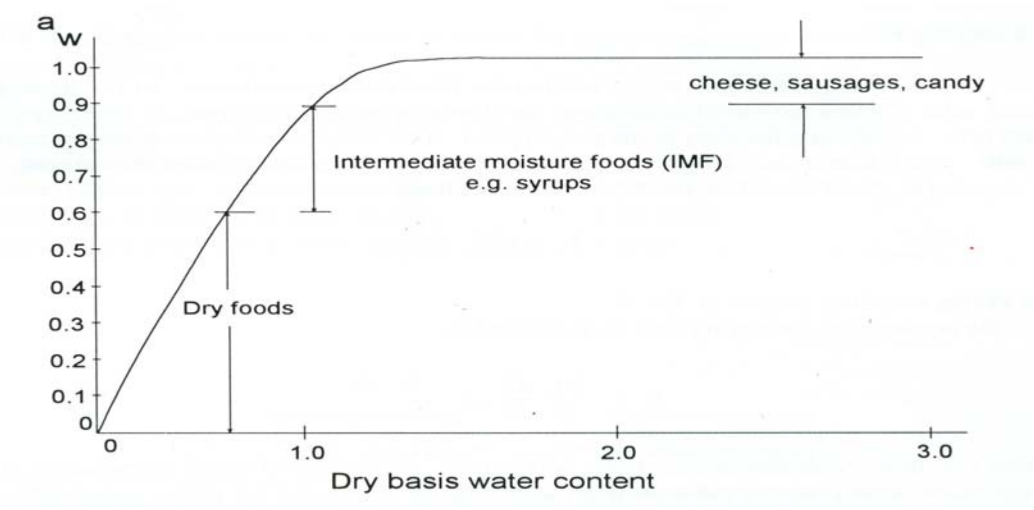

Figure 2.4. Relationship between water activity and moisture content (Cassens, 1994).

2.6. Textural Characteristics

Texture is an important parameter which defines the commercial value of meat and meat products. Texture and tenderness are rated as the most important of all the attributes of eating quality (Lawrie, 1998). Texture can be defined as a function of the size of the bundles of fibres into which the perimysial septa of connective tissue divides the muscle longitudinally (Lawrie, 1998). According to Weir (1960), the overall impression of tenderness to the palate includes texture, the initial ease of penetration of the meat by the teeth, the ease with which meat breaks into fragments and the amount of residue remaining after chewing. Hyldig and Nielsen (2001) reported that texture is a sensory parameter that only human being can perceive, describe and quantify. Even though there are contradictions among its definitions, it is clear that texture is the most important parameter which decides the value of meat products (mainly, in terms of consumer needs), particularly jerky.

2.6.1. Factors affecting texture

The texture of meat is affected by different pre and post-mortem factors. Several works were carried out to understand the textural properties of dry cured ham. Garcia-Rey et al. (2004)

studied the relationship between pH before salting and dry-cured ham quality and concluded that pH before salting is a good predictor for dry-cured ham quality. Ruiz-Ramirez et al (2005) reported that dry-cured ham muscles with lower salt content had lower hardness. Firmness, dryness and aroma of dry-cured ham improved with time (Buscailhon et al., 1994). Sensory and mechanical textural properties were not highly correlated for dry-cured ham (Guerrero et al., 1999). It was reported by Serra et al. (2004) that the hardness value of the dry-cured ham increased dramatically when the water activity and moisture content reached below 0.70 and 0.55 kg water/kg dry matter, respectively. Aranu et al. (1997) had found that an increase in the final month ageing temperature produced a softer and pastier texture in *Biceps femoris* muscle product. Resting time, brine injection, skinning and deboning also affected the final ham product.

Texture is strongly dependent on the meat protein level (Pietrasik and Shand, 2003). Salt concentration has an influence on the texture of the product (Arnau, 1991). Intra muscular fat content has a strong influence on the texture of dry cured ham (Ruiz-Carrascal et al., 2000). It was found out that deboning time along with cooking method also affect texture (Hsieh et al., 1980). Coarseness of texture increases with age of the animal (Lawrie, 1998). Significant negative correlation was reported between moisture content and hardness by Virgili et al. (1995) and Monin et al. (1995 & 1997) for dry-cured ham product. Temperature and relative humidity of the air affect the appearance and texture of dry-cured ham (Arnau and Gou, 2001; Arnau et al., 2003). Numerous studies of texture properties of meat muscles have been reported. Laakkonen et al. (1970) reported that meat tenderization and toughening during heating were due to the solubilization of the connective tissue and the denaturation of myofibrillar proteins, respectively. The relationship between toughness and cooking temperature was further studied by Davey and Gilbert (1974). They reported that toughness increases in two stages. The first increase was between 40 and 50^{o}C due to the denaturation of the contractile system of muscle, while the second stage was between 65 and 75^{o}C because of the collagen shrinkage. Similar results were found in other studies (Bouton et al., 1974; Ledward 1979). Most of the researchers studied the effect of physico-chemical composition on texture properties or the measurement of texture properties under a certain set of processing conditions. But, no studies were done to investigate the effect of different ingredients on textural properties of jerky.

2.6.2. Texture measurement techniques

Many attempts have been made to develop objective physical and chemical methods of assessing texture which would compare with subjective assessments by taste panels (Lawrie, 1998). Physical methods of measuring texture include the following; measuring the shear force (Warner, 1928; Kramer, 1957; Winkler, 1939), penetration force (Tressler et al., 1932; Lowe, 1934), force required to cut (Miyada and Tappel, 1956), force required to puncture (Lehmann, 1907; Volodkevitch, 1938), compression force (Sparring et.al., 1959) and tensile force (Wang et al., 1956). Chemical method involves the determination of connective tissue (Lowry et al., 1941; Neumann and Logan, 1950). In the enzymatic digestive method, enzymes such as papain, bromelain, ficin, trypsin and Rhozyme P-11 were employed (Kramer and Szczesniak, 1973).

Ruiz de Huidobro et al. (2005) have compared Warner-Bratzler texture profile and texture profile analysis on raw and cooked meat and reported that texture profile analysis (TPA) method is the best predictor of sensory texture for bovine meat. The Warner-Bratzler shear test measures the force necessary to shear a piece of meat, whereas TPA measures the compression force.

Texture is affected by drying jerky at high temperatures for extended periods of time (Calicioglu et al., 2002). It was reported by El-Shimi (1992) that the penetration force required is higher for microwave cooked roast beef than for conventionally cooked roast beef. Texture Technologies Corporation (2005) has tested the textural properties of restructured jerky against the traditionally made jerky. Very limited works have been reported on the textural characteristics of dried meat products. As the product quality mainly relies on its textural properties for market value, it is vital to investigate the effect of different parameters involved in its processing such as pH, water activity, salt content and method of drying. There was no literature found regarding these aspects. Emphasis has to be given to improve the textural characteristics of meat products.

2.7. Summary

As discussed earlier, there is a strong urge to understand the behavior of jerky while drying to optimize the process. As drying is the most important process controlling the final quality of the product, a deep knowledge of drying characteristics becomes vital. Increasing demand for this jerky increases the need for alternate and efficient drying method. As there are varieties of drying methods available, an energy efficient, rapid drying method needs to be further evaluated for its feasibility in jerky processing. Selection of the best method of drying beef jerky is desirable in order to achieve a better quality product in terms of texture, product safety and nutritional value. Increasing demand of soft jerky among women and children also urges the need for further research in product development of jerky. In this study, an attempt has been made to introduce the microwave drying / processing of beef jerky due to its rapid heating characteristics and unique manner of energy – material interaction effect.

CHAPTER III

MATERIALS AND METHODS

This chapter describes all the materials used for this research study. Also, it explains the experimental design plan and procedures carried out.

3.1. Materials

This section deals with the listing of several ingredients used in the preparation of the jerky samples and different drying systems, instrument and related equipment used in this research.

3.1.1. Materials used for sample preparation

The ingredients used for preparing all the samples studied are included below;

1. Meat –Beef *Biceps femoris* meat from Department of Food and Bioproducts Sciences, University of Saskatchewan, Saskatoon, SK
2. Glucono delta lactone, acidifier
3. Sodium chloride
4. Sugar
5. Sodium erythorbate
6. Prague™, curing agent (1 part sodium nitrite and 16 parts sodium chloride)

3.1.2. Equipment used for sample preparation

The following equipment were used in sample preparation of beef jerky.

1. Meat Grinder – Biro, Biro Mfd. Co. Marblehead, OH, USA
2. Vacuum Tumbler – H. Glass, Model VSM 150, Frankfurt, Germany

3. Industrial Blender – Berkel BA-20, Model ARM-02.
4. Food Extruder – Albert Handtmann Mfd. Ltd., Model VF-80, West Germany

3.1.3. Equipment used for drying experiments

The drying experiments were carried out in the following drying systems, listed below:

1. Modified microwave oven – Model Panasonic NNC 980W, 2005.
   a. Universal Multi channel Instrument, FISO Technologies Inc. Quebec.
   b. Labview, Version 6.0, National Instruments, Austin, TX
2. Forced air cross flow thin layer drying system
   a. Air Conditioning Unit- Bryant Mfd., Model AH-213, BMA Inc., Ayer, MA
   b. Axial fan, Model VA7D32, American Cool Air Corp, Jacksonville, FL
   c. Electronic transistor inverter- Model VFS7, Toshiba Corporation, Japan
   d. Relative humidity sensor- Watlow microprocessor controller
3. Smokehouse unit from Department of Food and Bioproduct Sciences, U of S.
   a. Alkar small batch smoke oven, Model 1000, Alkar, Lodi, WI, USA
   b. Combined exhaust and dust collector, American air filter, Model Type W- Roto-clone, Filtration Product Group, Louisville, KY

3.1.4. Equipment used for characteristics measurements

The following is the listing of the instruments used to measure physical-chemical and textural characteristics of beef jerky;

1. Vacuum oven -Fisher Vacuum Oven, Fisher Scientific. Co., Model 15, USA
2. Water activity meter- Aqua Lab, Model CX2, Decagon Devices Inc., WA, USA
3. Hunterlab Color Analyzer- Model Labscan-2, Hunters Associates Laboratory Inc., Virginia, USA.
4. pH Meter – Accumet, Model 15, Fisher Scientific, Pittsburgh, PA
5. Universal Texture Analyser – Model TA.XT2, Texture Technologies Corp., Scarsdale, NY
6. Instron Universal Testing Machine- Model 1011, Instron Corp., Canton, MA

3.2. Experiment Conducted to study the Effect of pH and Salt Content in Combined Microwave-Convection Drying

The effect of pH and salt content on beef jerky was explored for combined microwave-convection drying. The experimental design, methods of sample preparation and drying are explained in this section. Figure 3.1 shows the overall processing steps involved (sample procurement to end quality determination) in this experiment.

3.2.1. Experimental design

Samples having pH values of 5.65, 5.30 and 5.15 and sodium chloride content of 1.28, 2.28 and 3.28% (w/w) were tested to explore the effect of pH and salt content on combined microwave-convection drying of beef jerky. The experiment was designed using a randomized complete block design. All the experiments were done in two replicates. The treatment combinations are shown in Table 3.1.

Table 3.1. Treatment combinations

P1S1	P1S2	P1S3
P2S1	P2S2	P2S3
P3S1	P3S2	P3S3

where, P1, P2 and P3 refer to pH values of 5.65, 5.30 and 5.15, respectively and S1, S2 and S3 refer to salt content of 1.28, 2.28 and 3.28% (w/w), respectively.

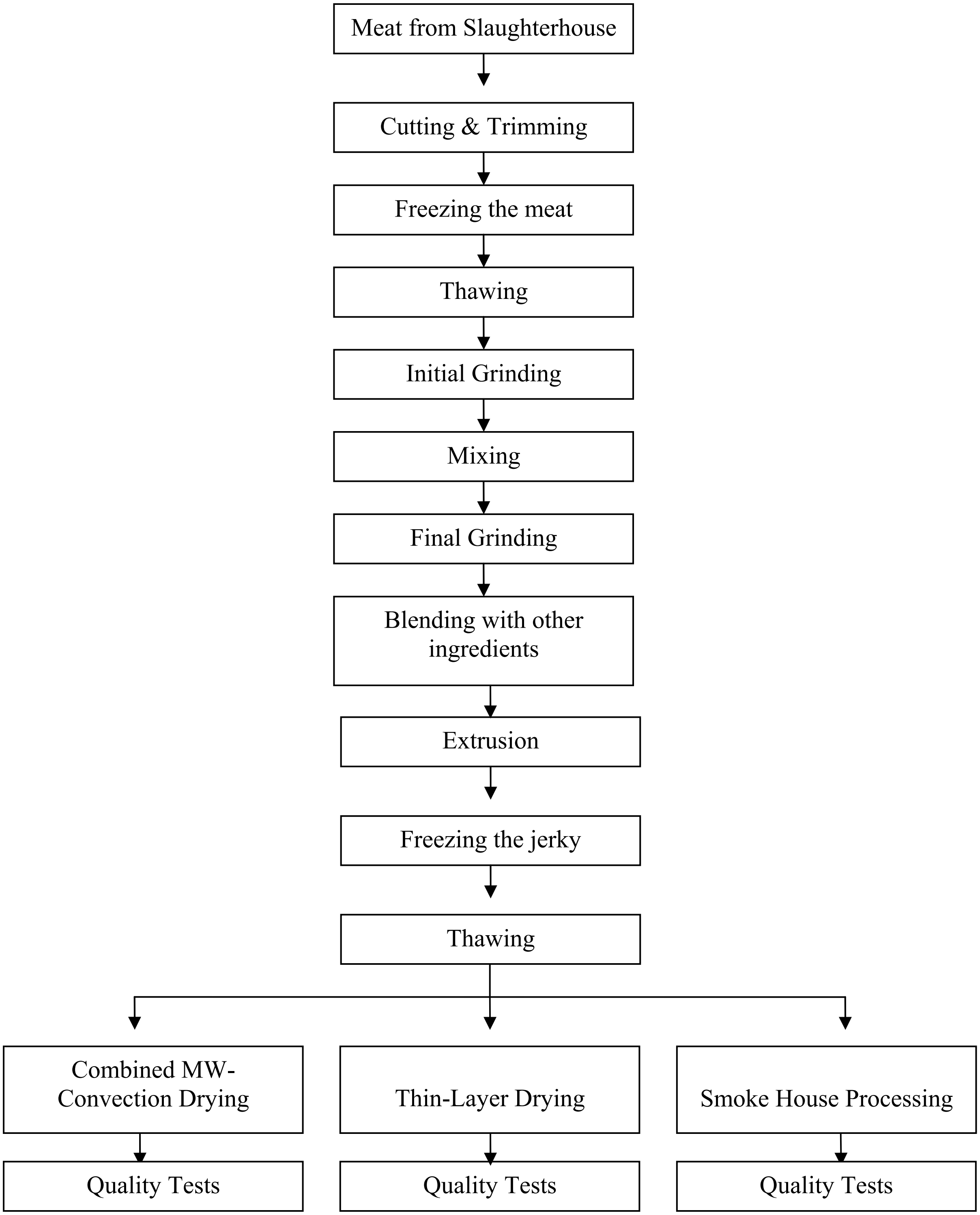

Figure 3.1. Flow chart indicating various stages of beef jerky preparation, drying and end product quality analysis.

3.2.2. Sample preparation

Beef *Biceps femoris* muscles were used to prepare the samples. The excess fat was trimmed off from the meat to prevent rancidity while drying. The meat received from the slaughterhouse was stored at -30 °C. The meat was thawed for 48 h to reach 4°C prior to sample preparation. As a first step of sample preparation, the meat chunks were ground using a kidney plate in a meat grinder (Biro, Biro Mfd. Co, Marblehead, OH, USA). To improve the homogeneity, the coarsely ground meat was blended in a vacuum tumbler (H. Glass, Model-VSM-150, Frankfurt, Germany) for 2 minutes. Again the meat was ground twice in a meat grinder using a blade with 1/8 inch slots. The other ingredients, according to the respective treatments shown in Table 3.2., were mixed with the meat at a low speed using the Industrial Blender (Berkel BA-20, Model ARM-02) for 105 s. To achieve the desired pH values of 5.65, 5.30 and 5.15, an industrial acidifier, glucono delta lactone, was added at 0, 0.5 and 1% (w/w), respectively, with the mixture while blending. The mixture was then fed into an industrial food extruder (Albert Handtmann Mfd. Ltd., model-VF-80, West Germany) to get 6 mm thick samples, which were then vacuum packed and stored in a -30°C blast freezer for further processing.

Table 3.2. Formulations of beef jerky samples with different treatments

Treatment	Meat (g)	GDL* (g)	Salt (g)	Sugar 2% (g)	Prague™ 0.3% (g)	Na Ery** 0.05% (g)	Water 3% (g)
P1S1	2817.92	0	21.58	60	9	1.5	90
P1S2	2787.92	0	51.58	60	9	1.5	90
P1S3	2757.92	0	81.58	60	9	1.5	90
P2S1	2802.92	15	21.58	60	9	1.5	90
P2S2	2772.92	15	51.58	60	9	1.5	90
P2S3	2742.92	15	81.58	60	9	1.5	90
P3S1	2757.92	30	21.58	60	9	1.5	90
P3S2	2757.92	30	51.58	60	9	1.5	90
P3S3	2727.92	30	81.58	60	9	1.5	90

where *Glucono delta lactone and **Sodium erythorbate

3.2.3. Combined microwave-convection drying

The frozen raw samples were thawed for 5 h at room temperature (23°C) prior to drying. Drying experiments were carried out in a laboratory-scale modified microwave oven (Model-Panasonic NNC 980W, 2005) which was designed to dry/heat with microwave, convective and a combination of convective and microwave energy. The specifications of the microwave oven are shown in Table 3.3. Each test was conducted with a sample size of 25 g. A setting of 295 W, pulse microwave (14 s ON and 7 s OFF), 70°C air temperature and 1.45 m/s air flow rate were used to dry the samples to 0.33 dry-basis moisture content. The time taken was noted and the weight loss was recorded online using a balance and Labview 6.0 (National Instruments, Austin, TX). The product temperature was monitored online during drying using a Universal Multi-channel Instrument (UMI, FISO Technologies Inc., Quebec) and Labview 6.0. One end of the four fibre optic probes was connected to the UMI and the other end of the probes was placed in different locations of the sample. Data were acquired using Labview 6.0. All the experiments were conducted in two replicates. Within each replication, three sets of data were collected for each treatment and the means were used for statistical analysis.

Table 3.3. Specifications of Panasonic NNC 980 W-Microwave oven.

Microwave Power Consumption	12.8 Amps, 1500 W
Heater Power Consumption	12.5 Amps, 1500 W
Microwave Output	1100 W
Heater Output	1400 W
Outside Dimensions	376 mm (H) x 606 mm (W) x 491 mm (D)
Oven Cavity Dimensions	242 mm (H) x 412 mm (W) x 426 mm (D)
Operating Frequency	2450 MHz

The dried samples were vacuum-packed and kept at 4ºC as a preventive measure from loss or gain of moisture.

3.3. Experiment Conducted to Study the Effect of Relative Humidity and Airflow Rate on the Thin-Layer Drying of Beef Jerky

The study to find the effect of relative humidity and airflow rate on thin-layer drying experiment was done with two relative humidities (40 and 15%) and airflow rates (1 and 1.45 m/s).

3.3.1. Sample preparation

For this experiment, 2.28% (w/w) salt content, 2% (w/w) sugar, 0.3% (w/w), prague^{TM}, 0.05% (w/w) sodium erythorbate and 3% (w/v) water were mixed with 3 kg of meat and the samples were prepared using the method described in section 3.2.2.

3.3.2. Forced-air thin-layer drying

The laboratory scale forced-air thin-layer cross flow drying unit (Figure 3.2) was used to dry the samples. This system consists of an air conditioning unit, a drying chamber, a vane axial circulating fan and a connecting duct system

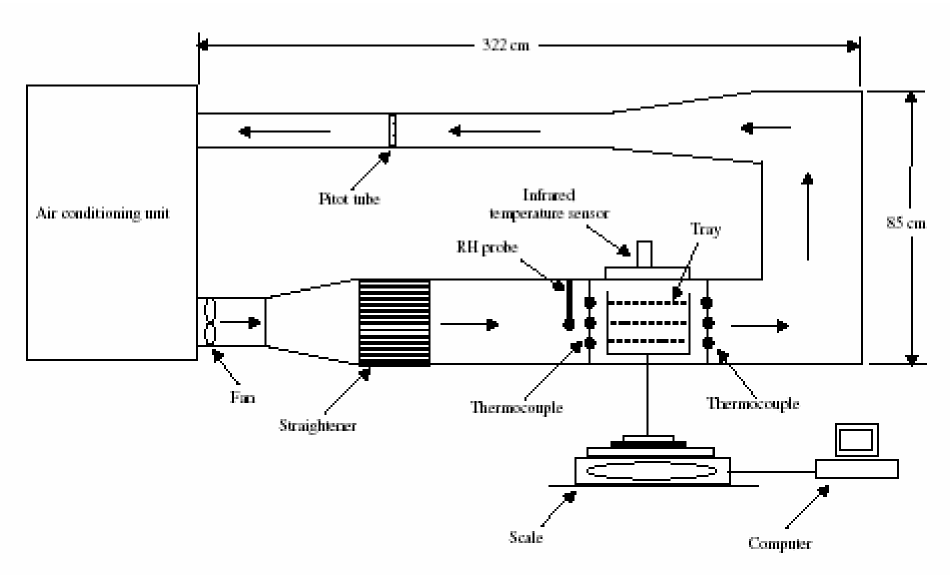

Figure 3.2. Schematic diagram of the thin layer cross-flow drying system.

The air conditioning unit (Model AH-213, BMA Inc., Ayer, MA) has an operating range of temperature between -17 and 200ºC and a relative humidity range of 2 to 98% which are controlled by a Watlow microprocessor controller with a temperature accuracy of ± 0.25ºC and the relative humidity accuracy of ± 2%. The axial fan (Model VA7D32, American Cool Air Corporation, Jacksonville, FL) re-circulates the conditioned air. The speed of the fan is controlled by a variable electronic transistor inverter (Model VFS7, Toshiba Corporation, Japan). The drying chamber consists of three rectangular fine wire-mesh drying trays, which are housed in the duct system insulated with 50.8 mm thick fiber glass.

The tests were conducted for 40 and 15% relative humidity and 1 and 1.45 m/s airflow rate with a constant air temperature of 80ºC. Samples were placed in the drying trays and product weight change was monitored online using Labview 6.0 (National Instruments, Austin, TX).

3.4. Smoke House Drying Experiment

3.4.1. Sample preparation

For this experiment, the jerky samples prepared with 2.28% (w/w) salt content, 2% (w/w) sugar, 0.3% (w/w) prague^{TM}, 0.05% (w/w) sodium erythorbate, 3% (w/v) water and 3 kg of meat were used.

3.4.2. Smoke house processing

A batch smoke oven (Model 1000, Alkar Corp., Lodi, WI, USA) shown in Figure 3.3, having a dimension of 228.6 m x 139.7 m x 154.9 m (height x depth x width), was used to process the jerky. The raw samples were placed on the trays of the scrolling truck with a screen size of 106.7 m x 106.7 m. The specialized oscillating air movement within the oven designed for the smoke house (shown in figure 3.4) improves the circulation of air within the chamber. The process is controlled by a JumboKPF-92 computerized controller. The dust and exhaust air is handled by type W roto-clone, American Air Filter, Filtration Product Corp., Louisville, KY. Table 3.4

shows the process parameters used in the preparation of beef jerky. The drying trials were done with two replications.

Figure 3.3. Batch smoke oven (www.alkar.com).

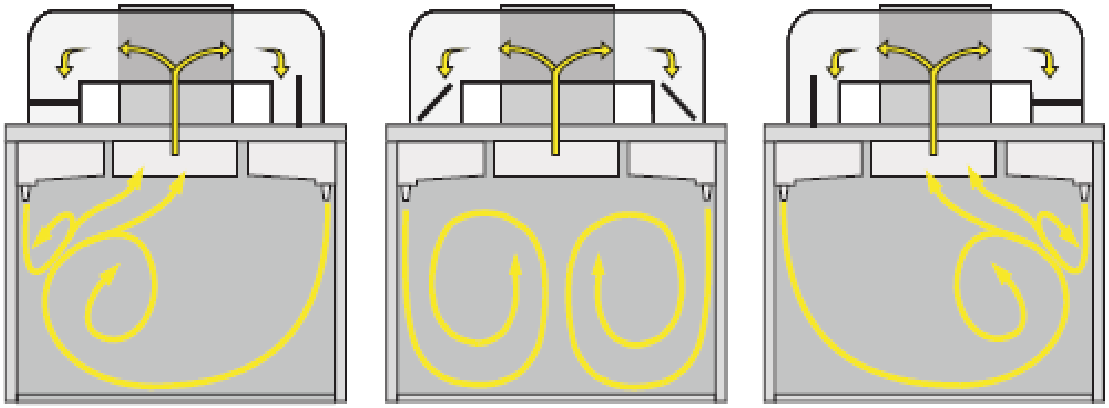

Figure 3.4. Airflow system of the small batch oven (www.alkar.com)

Table 3.4.Process parameters used for smokehouse processing.

Air Temperature,°C	Relative humidity, %	Cycle Time, min
40	30	20
55	30	20
60	30	20
65	45	20
70	40	20
76	45	30(Steaming)
50	25	Till end

3.5. Drying Characteristics

The different drying data obtained were fitted to the existing drying models shown in Table 3.5 using TableCurve 2D statistical software (Version 5.01, Systat Software Inc., San Jose, CA).

Table 3.5.Drying models.

Model No.	Name	Model Equation	References
1	Newton	$MR = \exp(-kt)$	Liu and Bakker-Arkema (1997)
2	Page	$MR = \exp(-kt^n)$	Zhang and Litchfield (1991)
3	Modified Page	$MR = \exp(-(kt)^n)$	White et al. (1981)
4	Wang and Singh	$MR = 1 + at + bt^2$	Wang and Singh (1978)
5	Henderson	$MR = a.\exp(-kt)$	Chhninman (1984)
6	Midilli	$MR = a*\exp(-k(tn))+b*t$	Midilli et al. (2002)

The moisture ratio (MR) is calculated as:

$$MR = \frac{M - M_e}{M_i - M_e} \tag{3.1}$$

where, M = moisture content (% db.); M_e = equilibrium moisture content (% db.) and M_i = initial moisture content (% db.)

3.6. End Quality Analysis: Physical-Chemical Characteristics Measurement

3.6.1. Moisture content measurement

Initial and final moisture contents of the sample were measured in accordance with the ASAE S353 (2003) method. The samples were passed through a 3 mm size screen of a precision grinder for three times. The ground sample was then mixed properly and a 5 g sample was placed in a covered aluminum dish which was put in a vacuum oven at 100°C under 100 mmHg absolute pressure for about 5 h until it reached a constant weight. Moisture content of each sample was measured three times.

3.6.2. Water activity measurement (a_w)

Water activity of the dried samples was measured using an Aqua lab water activity meter (Model CX2, Decagon Devices Inc., Washington, USA). The slices were cut into fine pieces for taking the measurements. Water activity of each sample was measured three times.

3.6.3. Shrinkage loss measurement

Initial and final volumes were measured and the *shrinkage coefficient* was calculated using

$$\textit{Shrinkage Coefficient} = 1 - \left(\frac{V_f}{V_i} \right) \times 100 \tag{3.2}$$

where V_f is the final volume and V_i is the initial volume of the sample (Trujillo et al., 2005). Samples were tested three times for each treatment.

3.6.4. pH measurement

The pH of jerky samples before drying was measured using a pH meter (Accumet-Model 15, Fisher Scientific). The pH meter was first calibrated with standard buffer solutions. Then, 20 g of sample with 80 ml of distilled water was mixed thoroughly in a household type blender for 30 s. The electrode was immersed in the mixed slurry and the sample pH was recorded. It was repeated three times for each treatment, with a fresh sample each time.

3.6.5. Color measurement

The color of the jerky before and after drying was measured to determine the appearance change. All the color measurements were done using a Hunterlab Color Analyzer- Labscan-2 (Hunter Associates Laboratory, Inc. Virginia, USA). The fresh or dried samples were placed in the 1.25 cm of area view and D65 was used as the illumination source. The CIE lab color scale (L*, a* and b*) value were recorded, where ‘L’ coordinate indicates lightness, which represents the greyness ranging from black (L = 0) to white (L = 100). The browning of the dried samples can be identified from the L value. The higher the L value, the less the product’s brown color (Rahman et al., 2002). The a-value represents the redness/greenness of the product. A positive a-value indicates the redness of the product and the coordinate ‘b’ indicates the yellowness (positive) or bluishness (negative). Three replicates were taken for each treatment and six readings were taken. To evaluate the effect of different drying temperatures on the overall combined color of the dried meat, the index ΔE as given in equation (3.3) (Tabil et al., 2001) was calculated by taking the color of fresh meat as the base value.

$$\Delta E = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2} \tag{3.3}$$

where, $\Delta L = L - L_{base}$, $\Delta a = a - a_{base}$ and $\Delta b = b - b_{base}$, and L, a, and b are the color coordinates of the sample and L_{base}, a_{base}, and b_{base} are the color coordinates of the control sample.

3.7. Textural Characteristics Measurement

3.7.1 Texture profile analysis

A Universal Texture Analyser TA.XT2 (shown in Figure 3.3) was used for texture profile analysis. TA.XT2 Texture Analyzer is a rugged bench-top movable instrument. Pieces of dried meat samples measuring 10 x 5 x 10 mm were placed parallel to the compression plate surface and compressed twice to 50% of their original height. The time between successive compressions was zero. A 25 kg load cell was used to compress the samples. Force-time curves were recorded at a crosshead speed of 5 mm/s.

Figure 3.5. Picture of texture analyser TA.XT2.

Hardness is defined as the maximum force reached during the first compression. *Springiness* is the measure of the ability of the product to retain its original dimension after the removal of the applied load. Other parameters were calculated from the force-time curve shown in Figure 3.4 using the following formulas (Texture Technologies Corporation, 2006):

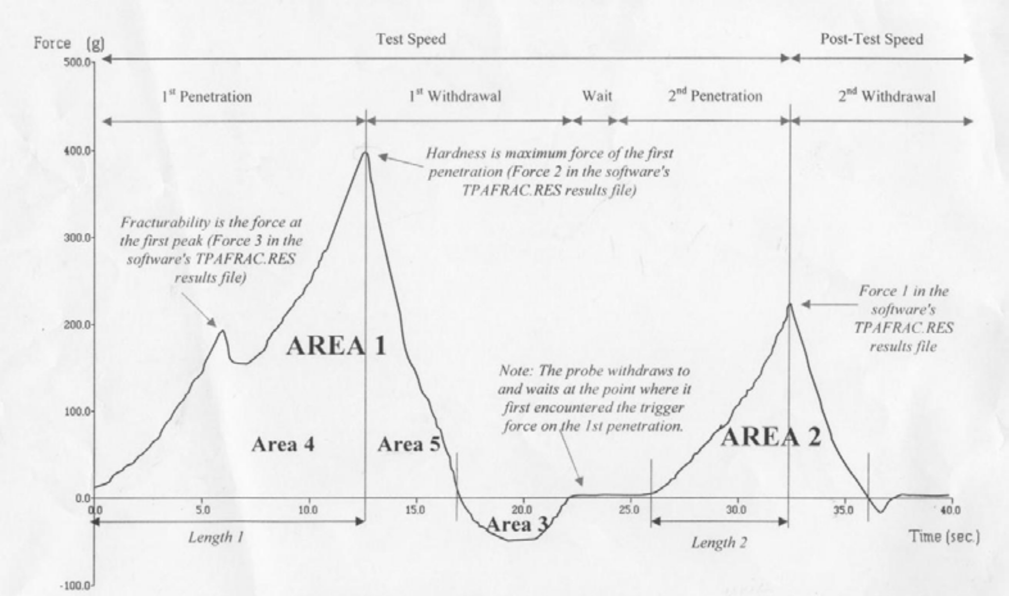

Figure 3.6. Texture profile analysis calculation for texture expert software (Texture Technologies Corporation, 2006)

$$Springiness = \frac{Length\ 2}{Length\ 1} \tag{3.4}$$

$$Cohesiveness = \frac{Area\ 2}{Area\ 1} \tag{3.5}$$

$$Gumminess = \left(\frac{Area\ 2}{Area\ 1}\right) \times Hardness \tag{3.6}$$

$$Chewiness = Gumminess \times \frac{Length\ 2}{Length\ 1} \tag{3.7}$$

$$Resilience = \frac{Area\ 5}{Area\ 4} \tag{3.8}$$

Cohesiveness is the ratio of second and first areas in the force-time curve. *Gumminess* is the product of hardness and cohesiveness. *Chewiness* is calculated by multiplying gumminess by springiness. *Resilience* is defined as the maximum energy per unit volume that can be elastically stored, which is represented by the area under the curve (areas 4 and 5 in Figure 3.6).

3.7.2. Puncture test

A puncture test was performed using a TA Texture Analyzer with a 3 mm diameter stainless steel probe. Jerky strips measuring 12.5 mm in length were laid over a 10 mm hole and the probe was pressed 10 mm into the sample at a crosshead speed of 0.5 mm/s. A 25 kg load cell was used. The probe was programmed to punch completely through the jerky each time. From each treatment, four samples were tested and the average value from each treatment was used in statistical analysis. Figure 3.7 shows the picture of the puncture test set up.

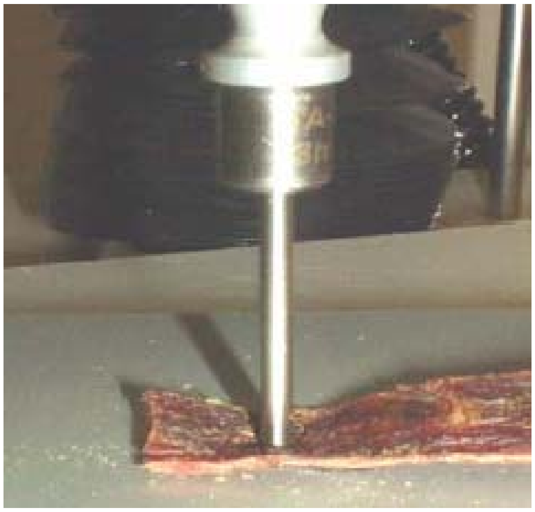

Figure 3.7. Picture of the puncture test apparatus

3.7.3. Tensile test

The tensile force and the energy necessary to pull the jerky apart were measured using an Instron universal machine (Model 1011, Instron Corp., Canton, MA). An initial grip separation was set to 50 mm and the crosshead speed was set to 60 mm/s. A 25 kg load cell was used to pull the strip apart. The tensile force, energy and elongation were recorded for each sample. From each treatment, five samples were tested and the average value from each treatment was used in statistical analysis.

3.8. Statistical Analysis

The experiment for investigating the effects of pH and salt on jerky processing was designed as a randomized complete block to avoid any sources of error. For data analysis and accurate results, the treatments were designed as factorial experiments. Factorial experiments allow investigators to concurrently evaluate the individual factors as well as their effects on each other. The effect of the factor on a dependent variable is termed the simple or main effects and the effect of one factor on another is termed as an interaction. The experiment conducted to investigate the effect of pH and salt content on combined microwave-convection drying, consisted of two main factors (pH, salt content) and three levels within each main factor. A two-factorial ANOVA was performed to find the effects of the main factors. Where the interaction between pH and salt content found significant, the single effects of each of the main factors were analyzed separately. The effect of these main factors was analyzed using a two-factorial ANOVA. The experiment was repeated twice and for each treatment three sets of data was recorded and their means were used in statistical analysis. The standard deviation and coefficient of variation of all the observed results were calculated by performing a ‘univariate’ test. The means were compared using Duncan’s multiple range tests with the p value less than 0.05.

The experiment conducted to find the effect of airflow rate and relative humidity in thin layer drying consisted of two main factors (relative humidity and airflow rate) and two levels within each main factor. This experiment was carried out using a randomized complete block design. It was done with two replicates and for each treatment three sets of data were recorded and used in statistical analysis. The data analysis was carried out with the null hypothesis that there would be interactions between variables. The effect of individual factors and interactions of each factor with each other were analyzed. When there was an interaction between variables, the single effect of each variable was done separately. The mean values were compared using Duncan’s multiple range tests. The ‘univariate’ test was used to calculate the standard deviation and coefficient of variation of all the observed results.

All the statistical analysis was done using SAS V8 for Windows (SAS Institute, Cary, NC). Type I error rate (α) was set at 0.05 for all statistical tests. Individual observations within each population were assumed to be approximately normally distributed.

The linear model for a randomized complete block used in this study is:

$$Yij = \mu + \iota_i + \beta_j + \varepsilon_{ij} \qquad (3.9)$$

where μ is mean, ι is treatment effect, β is block effect and ε is random element of variation. i ranges from 1 to the total number of treatments, and j from 1 to r, the number of blocks.

Table 3.6. Summary ANOVA table representing a randomized complete block design.

Source of Variation	df	Sums of squares (SS)	Mean square (MS)	F-value	P
Blocks	r-1	$r \mathbf{\Sigma} (\tilde{Y}_j - \tilde{Y})^2$	SS Blocks / (r-1)		
Treatments	t-1	$r \mathbf{\Sigma} (\tilde{Y}_i - \tilde{Y})^2$	SS Treatments / (t-1)		
Error	(t-1)(r-l)	SS (Total) – SS(blocks)+ SS(Treatments)]	SS Error /(r-1)(t-1)		
Total	rt-1	$\mathbf{\Sigma} (Y_{ij-} \tilde{Y})^2$			

CHAPTER IV

RESULTS AND DISCUSSION

Samples of jerky processed by different drying methods were analyzed for their characteristics. Physical, chemical, textural and drying properties were measured and analyzed to explore the influence of different treatments in jerky processing. The data acquired are presented and discussed in accordance with the objectives of this research study.

4.1. Effect of pH and Salt Content on Combined Microwave-Convection Drying

Three pH and three salt contents were tested to find the effect of pH and salt on beef jerky dried at a low microwave power level of 295 W (14 s ON and 7 s OFF), 1.45 m/s airflow rate and 70°C inlet air temperature in a combined microwave-convection drying oven. Drying, physical-chemical and textural characteristics of the dried jerky samples were measured and the data obtained were analyzed. As the combined effect of pH and salt were significant ($p < 0.05$), the single effects of pH and salt content in product quality were analyzed individually and the results are discussed in this section under different subheadings.

4.1.1. Initial moisture content

The initial moisture content of beef jerky samples measured prior to drying are presented in Table 4.1. The initial wet basis moisture content of the samples of the different treatments ranged from 68.49 to 71.95%. Yet, these differences in data were not statistically significant ($p < 0.05$). This shows that the initial moisture contents of the samples were not affected by the alteration of sample pH or the modification of the salt content. Also, these results show that the experiment was conducted with samples having essentially the same initial moisture content.

Table 4.1. Initial wet basis moisture contents of the jerky samples prior to drying with different pH and salt content levels.

pH	Salt Content (% (w/w))	Moisture Content		
		Mean (% wb.)	SD (% wb.)	CV (%)
5.65	1.28	71.37 a	0.48	0.67
	2.28	70.94 a	2.27	3.20
	3.28	69.87 a	1.74	2.49
5.30	1.28	71.96 a	0.95	1.33
	2.28	69.48 a	0.15	0.22
	3.28	69.82 a	1.14	1.64
5.15	1.28	69.93 a	0.21	0.30
	2.28	68.84 a	1.55	2.25
	3.28	68.51 a	0.65	0.94

Means in the same column with different letters are significantly different ($p < 0.05$).

4.1.2. Drying characteristics

The drying characteristics data of samples with different pH and salt contents are exhibited in Table 4.2. Statistical analysis revealed significant differences due to pH, salt and their interaction.

The average drying rate of the samples ranged between 15.35 and 19.50 kg of water per kg of dry matter /h. Drying rate was influenced by both pH alteration and salt content. Addition of more salt improved the process rate. Drying rates of samples with high salt content (3.28%) were significantly different from 1.28 and 2.28% salt content samples at sample pH of 5.65, whereas the increase in salt from 1.28 to 2.28% did not affect the drying rate of the samples with pH 5.30. At the same pH level (pH 5.15), the drying time was reduced from 6.75 to 5.50 min by increasing the amount of salt added from 1.28 to 3.28%. On the whole, samples with high salt content showed improved drying rate and drying time.

Table 4.2. Effect of pH and salt content on drying characteristics of beef jerky dried under combined microwave-convection drying

pH	Salt Content (% (w/w))	Average Drying Rate (kg of water per kg of dry matter per h)	Drying Time (min)
5.65	1.28	15.35 ± 0.40 e	8.50 ± 0.22 a
	2.28	16.84 ± 0.33 d	8.25 ± 0.16 b
	3.28	16.96 ± 0.45 d	6.50 ± 0.16 e
5.30	1.28	17.17 ± 0.38 c d	7.25 ± 0.16 c
	2.28	17.15 ± 0.40 d	6.75 ± 0.16 d
	3.28	19.33 ± 0.47 a	6.00 ± 0.16 g
5.15	1.28	17.54 ± 0.41 c	6.75 ± 0.16 d
	2.28	18.66 ± 0.47 b	6.25 ± 0.16 f
	3.28	19.50 ± 0.56 a	5.50 ± 0.16 h

Means in the same column with different letters are significantly different ($p < 0.05$).

Dielectric properties of salt have a major effect on drying of beef jerky. The dielectric loss factor reported by Lyng et al. (2005) 1.5 and 2.5% (w/w) salt are 29.19 and 36.37 at 2540 MHz frequency, respectively. The dielectric loss factor of beef (13.7) was increased to 24.4 when it was blended with 1.5% (w/w) salt (Lyng et al., 2005). Also Lyng et al. (2005) reported the dielectric loss factor of water solution with 0.5% (w/w) salt as 15.6 at 2450 MHz frequency, where the dielectric loss factor of the distilled water was found as 10.3 only. As the dielectric loss factor of the jerky samples with 3.28% salt content is higher than 1.28 or 2.28% salt content, the energy absorbed by the product becomes higher in 3.28% salt content sample. This leads to more heating and a shorter drying time. A study done by Rozzi and Singh (2000) on starch solutions containing salt revealed that the microwave heating profile of the samples containing salts versus those without salt had a significant difference. Also Tang (2005) reported a change in the dielectric properties of mashed potato with 0.8 and 1.8% (w/w) salt. He has reported that the dielectric loss factor was increased from 16.3 to 19.4 by the addition of more salt.

The average rate of drying of the samples with 1.28% salt and pH 5.65 was 15.35 kg of water per kg of dry matter per h, whereas the sample whose pH was reduced to 5.15 by the addition of glucono delta lactone was improved to 17.54 kg of water per kg of dry matter per h. These trends were found within the experimental data set. The effect of pH within lower pH levels was found insignificant for 1.28% and 3.28% salt content samples, where for 2.28% salt content samples the effect within higher pH levels were to be insignificant. Overall, lowering the pH has increased the average drying rate regardless of their salt content. Within the nine treatment combinations, samples with 3.28% salt content and lowered sample pH level of 5.30 and 5.15 were found to have the highest drying rate of 19.33 and 19.50 kg of water per kg of dry matter per h. Time taken to dry the samples to the same final moisture content of 0.33 db were significantly reduced with the change in sample pH and amount of salt added. Samples having low pH and higher amount of salt took less time (5.50 min for samples having pH 5.15 and 3.28% salt content) to dry than control samples (8.50 min for samples having pH 5.65 and 1.28% salt content). Within the same salt content (1.28%), the drying time was minimized from 8.5 min (pH 5.65) to 6.75 min (pH 5.15). Lower pH samples had dried faster than higher pH samples.

Water holding capacity will be minimum at the pH range between 5.0 and 5.1 (Cassens, 1994). It was reported that at this pH range, the isoelectric point of the major muscle protein occurs. Isoelectric point can be defined as the point where the positive and negative charge groups of protein becomes equal. As a result, water molecules can't reside in that compact structure and become immobilized. When the positive or negative charges increase, these charged protein groups tend to repulse and in turn leave more space for the water molecules. Thu, the water holding capacity increases with change in pH. In this study, the samples with pH 5.15 and 5.30, which are closer to the isoelectric point, due to the net charge effect, showed reduced the water holding capacity. Thus they dried faster.

Also, addition of glucono delta lactone, indirectly influences the sample pH and affects the drying behaviour as the result. Glucono delta lactone (GDL) is a cyclic ester, which produce gluconic acid when it hydrolyses (Trop and Kushelevsky, 1985). But, GDL and gluconic acid being a weak acid with pKa value of 3.7, they are in equilibrium all the time. Gluconic acid (GCOOH) in the presence of water ionizes and delivers $GCOO^-$ and H_3O^+. These products are not completely ionized, explained by their lower pKa value. However, the pH of the meat sample changes according to the concentration of H_3O^+ produced and rate of hydrolysis of GDL. Thus, GDL influence the drying characteristics of beef jerky. The ionization and polarity of gluconic acid and its salt (GDL) in water helps in producing more heat in the microwave environment. Since hydrolysis of gluconic acid is accelerated due to higher temperature, producing more polarized molecules, once again the friction caused by these di-polar molecules resulting in high temperature and heating. Due to these combined effects, moisture evaporation increases and leading to improved drying rate and reduced drying time.

The drying data were fitted into several standard drying models to predict the drying pattern of the jerky. Most of the treatments data followed the Page equation and others followed the Wang and Singh equation. Drying constants for different treatments were derived and displayed in Table 4.3. Saskatoon berries dried under combined microwave-convection mode had followed the Midilli equation (Reddy, 2006). The K and n values found for beef jerky samples, which fitted with the Page equation, have shown comparable results with other products dried in microwave power. Spinach dried in microwave energy fitted well with the Page equation and shown the drying constant K as 0.0159 min^{-1} and exponential value n, as 1.629 at 160W microwave power and K as 0.0436 min^{-1} and n as 1.904 at 350 W microwave power (Ozhan et al., 2007). Mushrooms dried in a combination of microwave (250 W)-vacuum (10 kPa) fitted to Page model have shown K value as 0.099 min^{-1} and n as 1.289 (Giri and Prasad, 2007).

Table 4.3. Drying equations of different treatment samples dried under combined microwave-convection drying

pH	Salt Content (% (w/w))	Drying Model	R^2	Std. Error	Drying Constants (K in min^{-1})
5.65	1.28	Wang and Singh	0.995	0.018	$a1$=-0.1114; $a2$=0.0016
	2.28	Page	0.980	0.036	K=0.1912 ; n=1.0417
	3.28	Page	0.972	0.050	K=0.1244; n=1.4719
5.30	1.28	Wang and Singh	0.996	0.015	$a1$=0.1551; $a2$=1.1951
	2.28	Page	0.965	0.051	K=0.1179; n=1.3606
	3.28	Page	0.970	0.048	K=0.2243; n=1.1632
5.15	1.28	Page	0.998	0.002	K=0.3484; n=0.8977
	2.28	Page	0.995	0.022	K=0.1201; n=1.6179
	3.28	Wang and Singh	0.990	0.027	$a1$=-0.2800 ; $a2$=0.0226

The drying curves shown in Figures 4.1 - 4.3 illustrate the different trends followed by the samples with different pH while drying. At 1.28% salt content, the drying curve of the samples having pH 5.65 and 5.30 fitted well with Wang and Singh equation (Wang and Singh, 1978), whereas for the samples having pH 5.15, Page's equation (Zhang and Litchfield, 1991) fitted the best. Overall, it was found that lowering the pH increased the drying rate, which in turn reduced the time taken to dry the samples. Moisture removal at first 2-3 minutes of drying was found to be high in all the treatments. This must be because of the high initial moisture content of the samples, which absorbs more microwave energy. Due to the high heating rate of microwaves, the jerky samples followed a high constant rate of moisture removal throughout the drying period. The samples with low pH had shown high moisture removal rate and hence they dried more rapidly than the others.

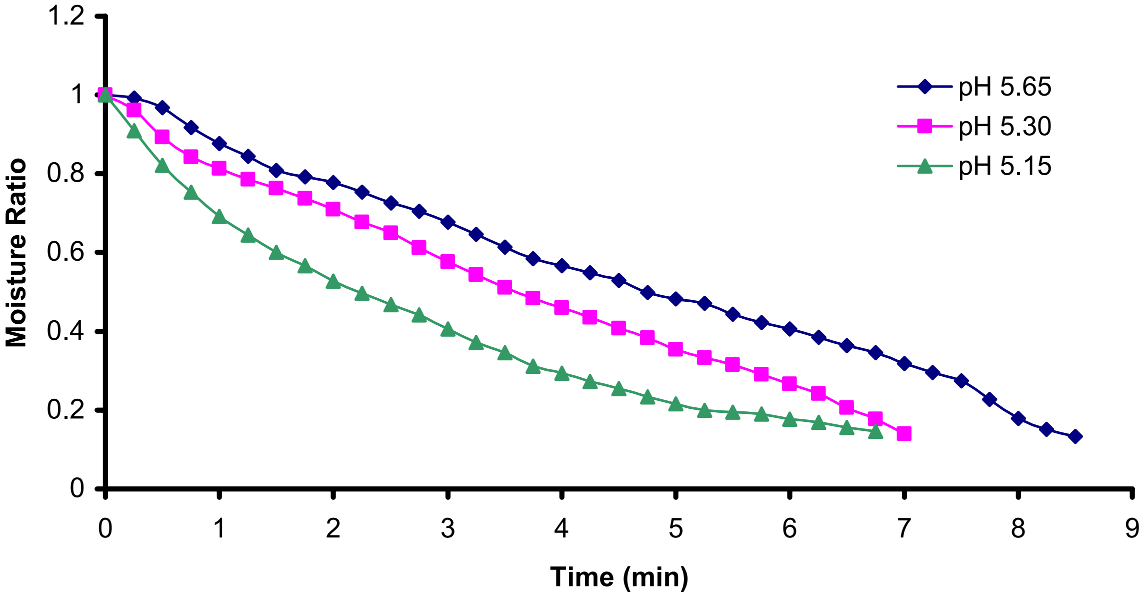

Figure 4.1. Drying curves of jerky samples having 1.28% (w/w) salt content with pH 5.65, 5.30 and 5.15 levels dried in combined microwave-convection drying.

For jerky with 2.28% salt content, the moisture removal rate was high at the beginning and then due to the interaction of salt and microwaves, the drying rate became more rapid. Due to the combined effect of salt and pH, the samples have shown higher moisture removal at the beginning and a high constant moisture removal rate was followed until the end of the drying process. Samples with 3.28% salt content also behaved similarly to those with 2.28% salt while drying. In the case of samples with 3.28% salt, the drying was even faster compared to 2.28% salt content samples, likely due to the higher dielectric loss factor contributed from the addition of 3.28% salt.

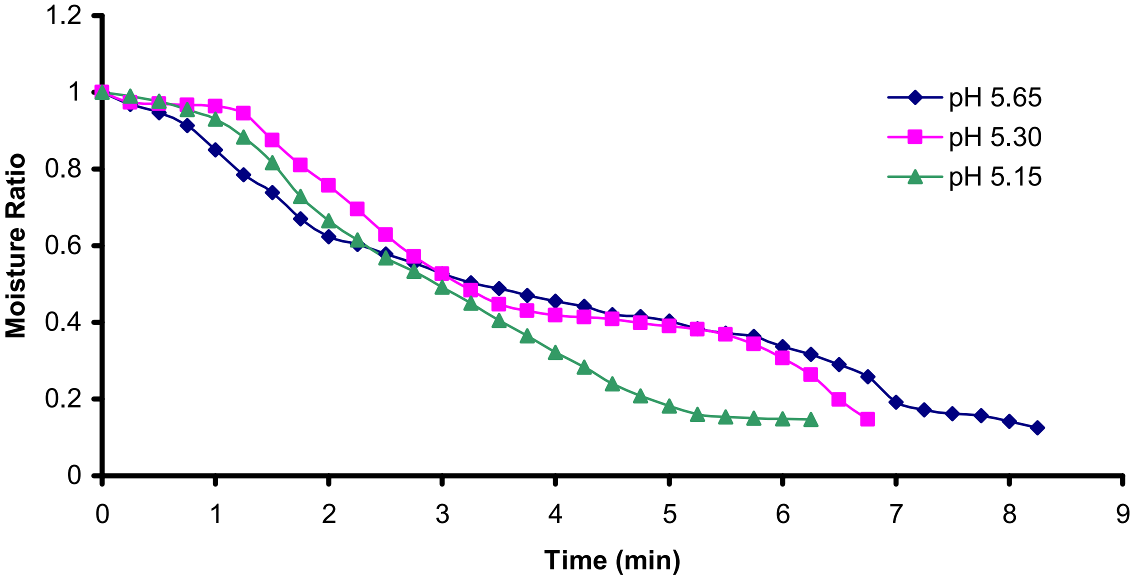

Figure 4.2. Drying curves of jerky samples dried in combined microwave-convection drying showing the effect of pH at 2.28% (w/w) salt.

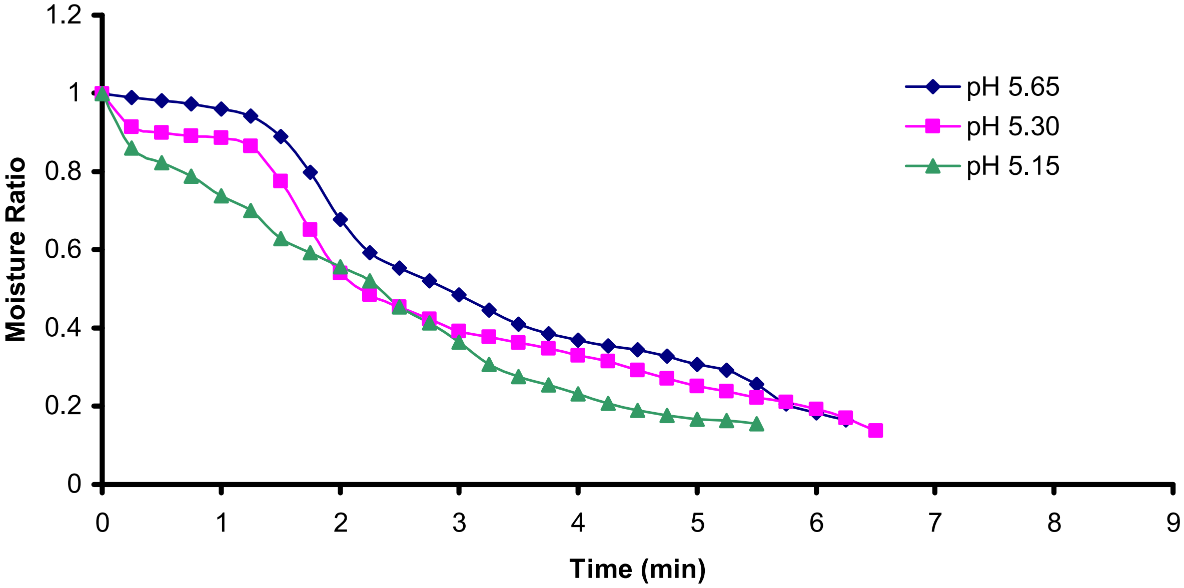

Figure 4.3. Drying curves of jerky samples dried in combined microwave-convection drying showing the effect of pH at 3.28% (w/w) salt.

Figure 4.4 shows the drying rate curves of the samples with different salt content at pH 5.65 and revealed the effect of salt content in their drying behavior. Drying of the jerky samples with 1.28% salt content, started with a high moisture removal rate and at this period the surface water was evaporated due to the high heating capability of microwave energy and then the drying was carried out with a less drying rate constantly till the end. Samples with 2.28% salt content have followed a similar trend as 1.28% salt content samples. But, for the sample with 3.28% salt content initial moisture removal was slow and then the moisture content was dropped sharply due to the higher absorption of microwaves and high internal heat created.

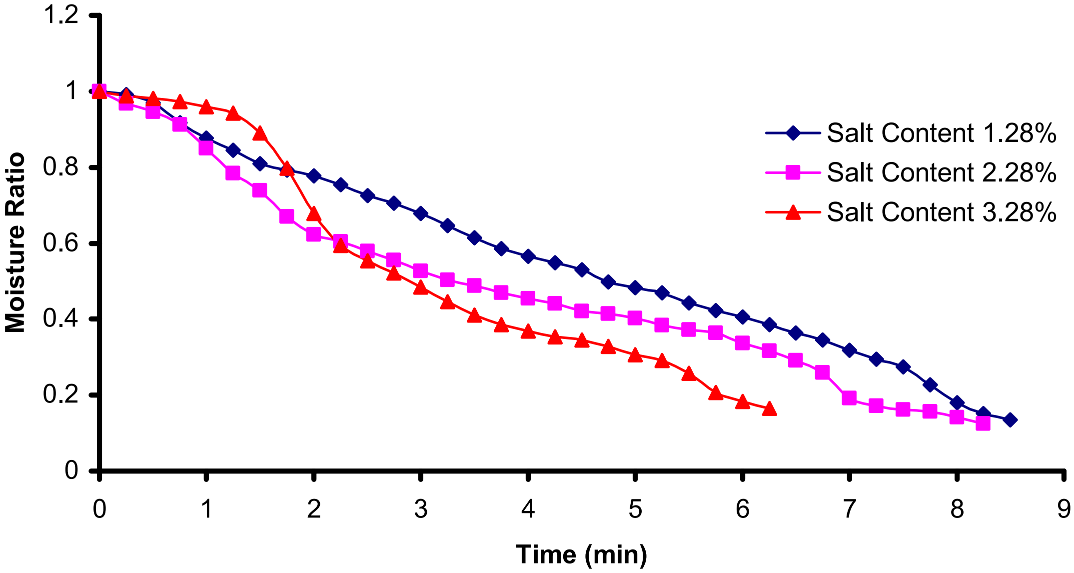

Figure 4.4. Drying curves of samples dried in combined microwave-convective drying mode, showing the effect of salt content at pH 5.65.

Drying curves of the samples dried with different salt contents at pH 5.30 are shown in Figure 4.5. For the samples with 1.28% salt content, drying rate was maintained the same throughout the process except at the beginning. Initial moisture removal rate were found to be higher compared to the rest of the drying period. Samples with 2.28% behaved similarly. The drying rate was high at the beginning of the drying, and then the drying rates were dropped sharply to maintain a constant rate. However, the 3.28% salt content samples had high drying rates throughout drying than the others.

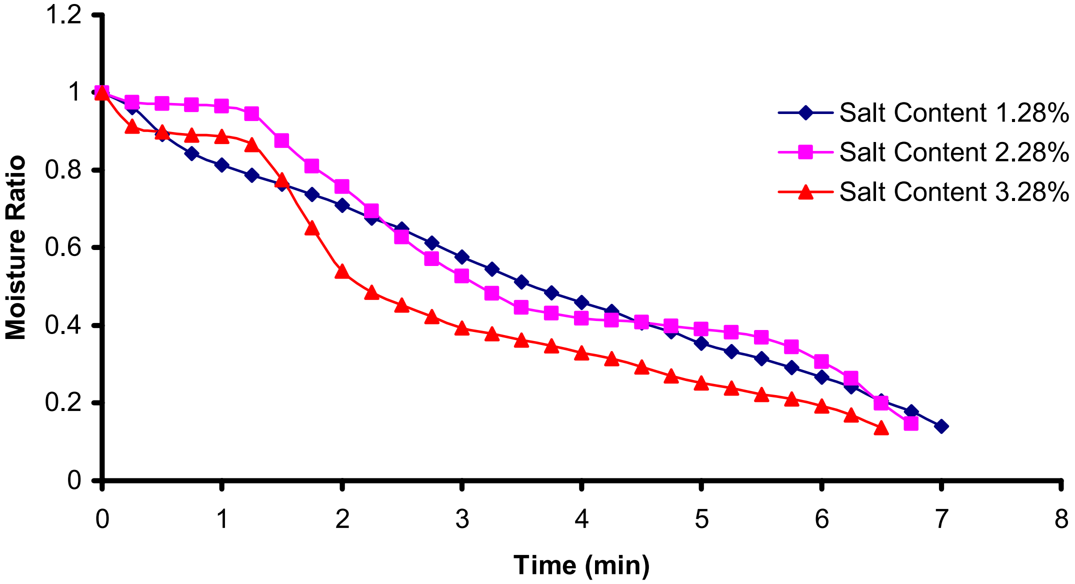

Figure 4.5. Drying curves of samples dried in combined microwave-convective drying mode, showing the effect of salt content at pH 5.30.

Drying rate curves shown in Figure 4.6. illustrate the effect of salt content at pH 5.15 value on beef jerky. All the samples behaved similarly, except 2.28% salt content sample had a slow drying stage at the beginning then, the drying rate has reached its maximum after 2 mins and then dropped to follow a constant drying rate. The drying rate of the samples at pH 5.15 was significantly higher than high pH samples due to the combined ionic effects of salt and pH and the increased heating in the presence of microwave energy.

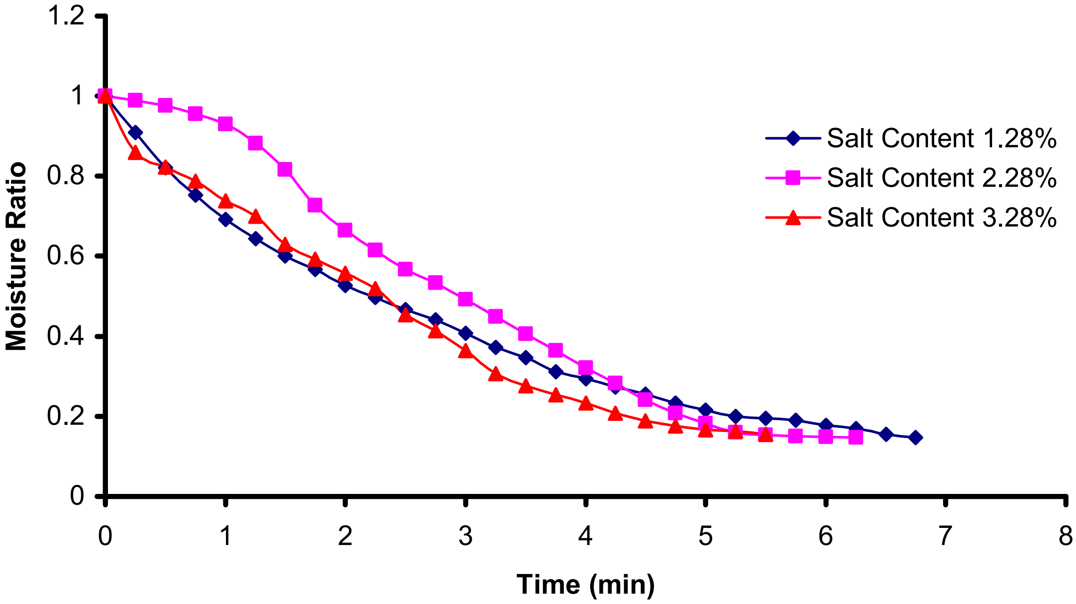

Figure 4.6. Drying curves of samples dried in combined microwave-convective drying mode, showing the effect of salt content at pH 5.15.

Coriander leaves dried in a microwave oven showed the similar trend of higher initial moisture removal rate which was followed by a constant rate period (Shaw et al., 2007). Shaw et al. (2007) also reported that coriander hadn't followed any falling rate period during drying. The observations from drying of beef jerky also show similar drying characteristics. This can be explained by the higher heating of microwaves which removed the moisture rapidly and thus products dried faster. pH and salt have significantly influenced the drying characteristics. However, the samples followed the same trend of higher initial drying rates.

The drying characteristics observed for beef jerky under microwave-convection combination drying have shown that by lowering pH and increasing salt content the drying characteristics can be improved. Samples with low pH (5.15) and high salt (3.28%) were found to exhibit a higher drying rate and the shortest drying time.

4.1.3 Product temperature

Figure 4.7 shows the variation in the product temperature during drying of samples with three different pH values at 1.28% salt content. It was observed that the product temperature of the samples having pH 5.65, 5.30 and 5.15 reached to the maximum of 81.4°C, 88.2°C and 93.4°C respectively during drying. Apparently, it took 2.75 and 2.50 mins to reach a constant temperature for pH 5.65 and 5.30 samples, whereas in the case of pH 5.15 samples, it took only 1.25 mins. Lower pH samples have shown higher product temperature. The study done on smoke house processing of beef jerky by Unklesbay (1999) revealed that thermal diffusivity values of the beef jerky were in the range of 1.65 to 0.89 10^{-7} m^2/s.. This study was concluded as the values for the different pH samples were quite variable and did not follow a linear trend. In this current study, this property was not measured. But, the temperature rise in lower pH samples can be explained by the interaction of microwaves in high acid materials. As the ionic effect is higher in high acid products, a significant amount of heat was produced within the samples with lower pH.

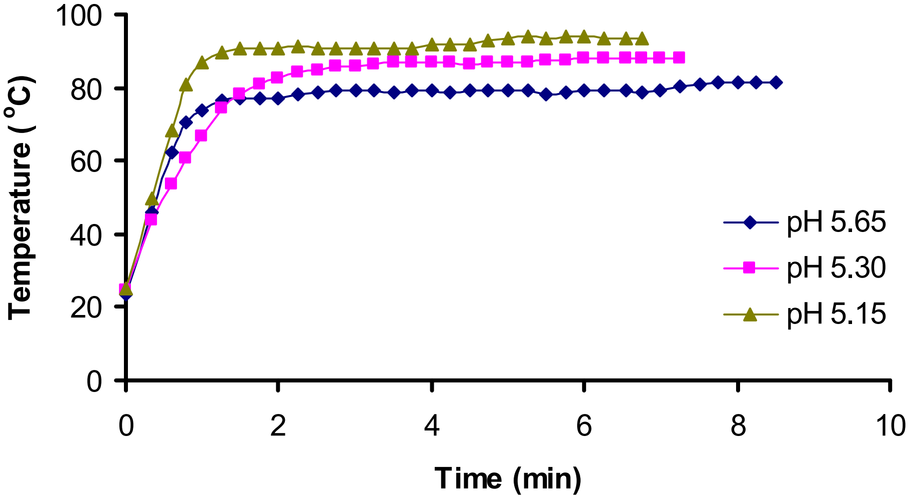

Figure 4.7 Effect of pH on product temperature of beef jerky samples with 1.28% salt content dried in combined microwave-convection drying.

The same trend was followed in the samples at 2.28 and 3.28% salt content too (Figure 4.8 and 4.9). The samples with pH 5.65, 5.30 and 5.15 reached a maximum product temperature of 86.1°C, 91.5°C and 97.0°C, respectively, at 2.28% salt content (Figure 4.8). At 3.28% salt content, the product temperature of beef jerky samples with control, pH 5.30 and 5.15 reached to 101.4°C, 101.5°C and 104.7°C, respectively (Figure 4.9).

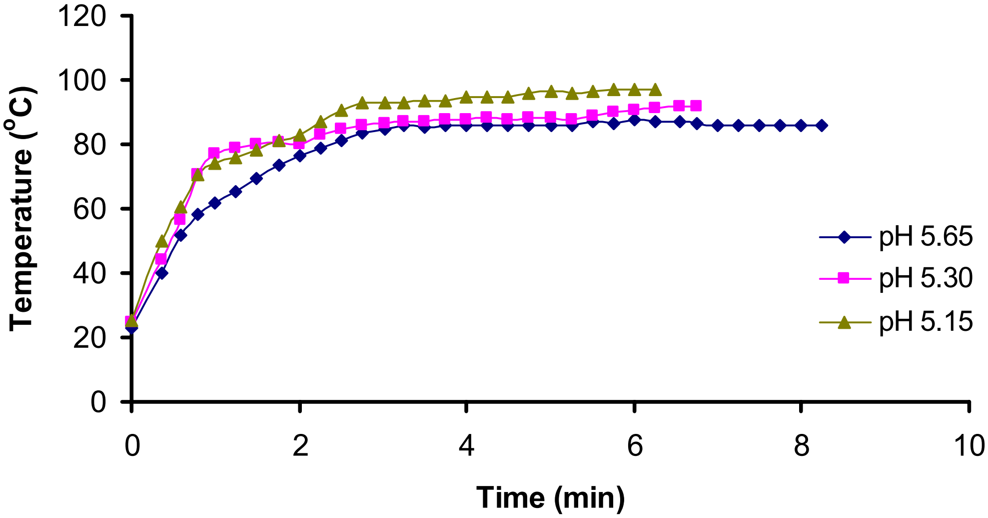

Figure 4.8 Effect of pH on product temperature of beef jerky samples with 2.28% salt content dried in combined microwave-convection drying.

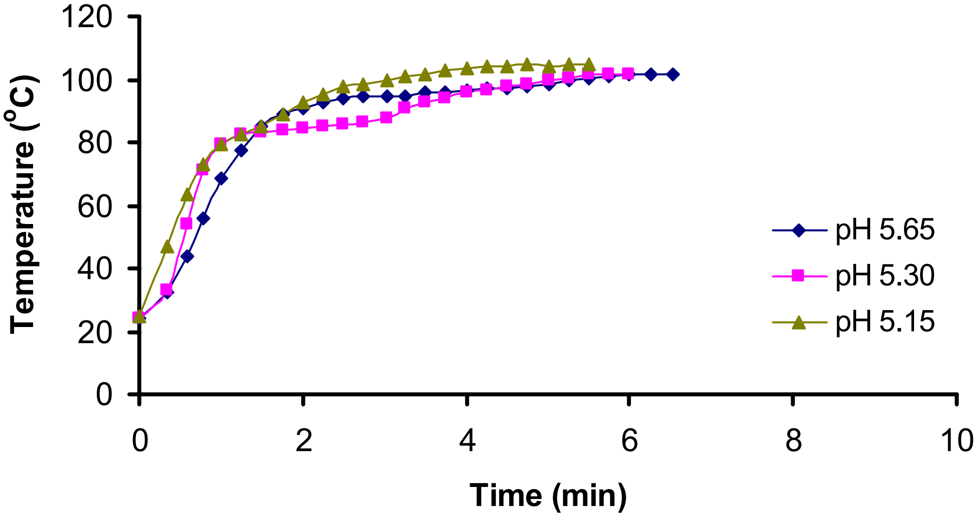

Figure 4.9 Effect of pH on product temperature of beef jerky samples with 3.28% salt content dried in combined microwave-convection drying.

The effect of salt content on product temperature in combined mw-convection drying was found to be significant. Figure 4.10 shows the temperature pattern followed by the samples for different salt content at pH 5.65. It was observed for the pH 5.65 samples that the product temperature of the samples having 1.28, 2.28 and 3.28% salt content reached to a maximum of 81.4°C, 86.1°C and 101.4°C respectively during drying. Product temperatures were increased with the amount of salt added to the sample. The higher dielectric loss factor of samples with additional salt has caused more absorption of microwaves and the internal heating of the samples with higher salt content were higher than others.

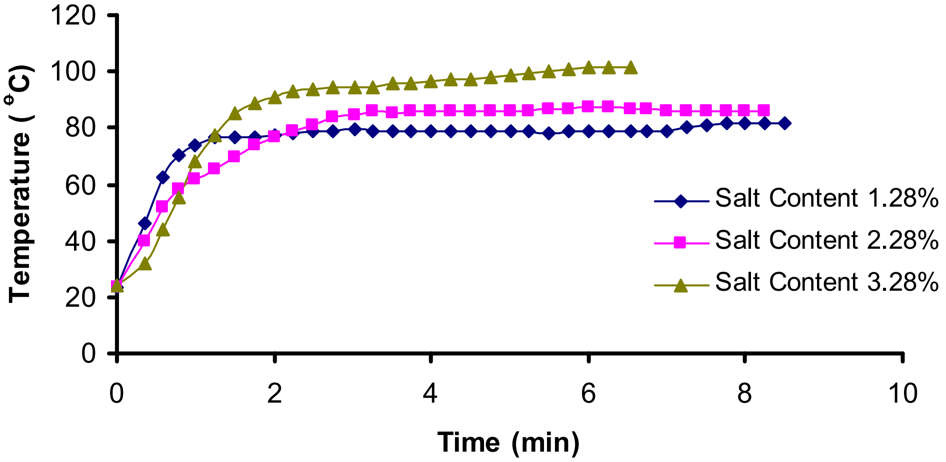

Figure 4.10. Effect of salt content on product temperature of beef jerky samples dried in combined microwave-convection drying at pH 5.65.

Effect of salt content on product temperature trend at pH 5.30 and 5.15 are presented in Figures 4.11 and 4.12. The product temperature of the samples with 5.30 and 5.15 pH were also influenced by the addition of salt. Samples with pH 5.30 reached to a maximum of 88.2°C, 91.5°C and 101.5°C, where samples with pH 5.15 reached to 93.4°C, 97°C and 104.7°C product temperature. It was also observed that addition of 1.28 or 2.28% salt content didn’t make much difference in product temperature. But, addition of more salt had increased the temperature noticeably high. All the product temperatures that were reached in combined microwave-convection drying of beef jerky were above 71°C, which assures the product safety as per the USDA (2003) recommendation.

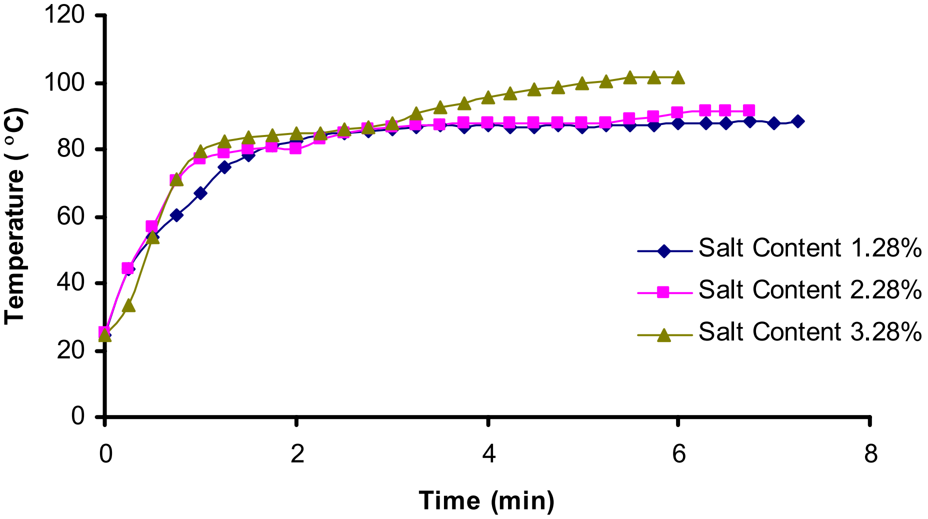

Figure 4.11. Effect of salt content on product temperature of beef jerky samples dried in combined microwave-convection drying at pH 5.30.

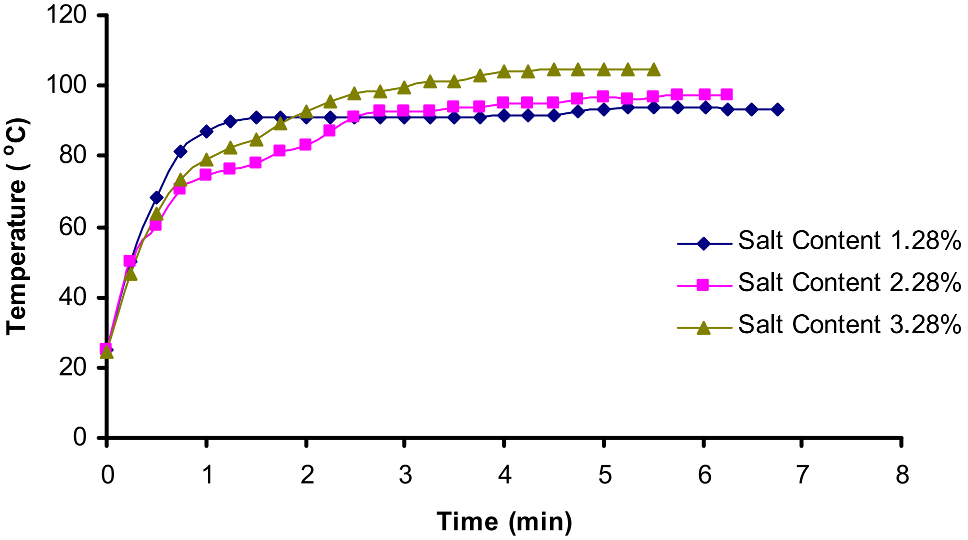

Figure 4.12. Effect of salt content on product temperature of beef jerky samples dried in combined microwave-convection drying at pH 5.15.

It was observed from the jerky samples dried in combined microwave-convection that low pH and high salt content samples have reached higher product temperatures than others. The ionic effect of higher acid samples and higher dielectric loss factor of higher percentage of salt added, increased the internal heating of the sample in microwave energy and thus the product temperature were higher than other treatments.

4.1.4. Physical and chemical characteristics

The effects of pH and salt content on shrinkage loss, weight loss and water activity of jerky are shown in Table 4.4.

Table 4.4. Physical-chemical characteristics of beef jerky dried under combined microwave-convection drying.

pH	Salt Content (% (w/w))	Shrinkage (%)	Weight loss (%)	a_w
5.65	1.28	32.14 ± 1.75 h	56.54 ± 0.00 f	0.86 ± 0.00 a
	2.28	37.77 ± 0.29 g	57.10 ± 0.10 e f	0.82 ± 0.01 b
	3.28	48.32 ± 0.57 e	58.15 ± 0.28 d	0.80 ± 0.00 c
5.30	1.28	42.34 ± 0.75 f	57.59 ± 0.36 d e	0.85 ± 0.01 a
	2.28	52.11 ± 0.54 c	59.38 ± 0.22 c	0.78 ± 0.00 c d
	3.28	53.33 ± 0.41c	60.60 ± 0.56 a	0.75 ± 0.01 e
5.15	1.28	49.84 ± 0.85 d	59.10 ± 0.34 c	0.79 ± 0.00 c d
	2.28	54.95 ± 0.61 b	60.36 ± 0.30 b	0.77 ± 0.01 d
	3.28	60.44 ± 1.89 a	62.57 ± 0.51 a	0.68 ± 0.00 f

Means in the same column with different letters are significantly different ($p < 0.05$).

Shrinkage and weight loss were found to be significantly influenced at constant moisture content. The lower pH samples had higher shrinkage and weight loss. As the moisture removal rate was higher in lower pH samples compared to higher pH samples, more dimensional deformation occurred in samples with lower pH. The dimensional change varied from 32.14 to 49.84% when pH of the samples was changed from 5.65 to 5.15 at 1.28% salt content. The shrinkage value observed in jerky with 2.28% salt content was increased ($p<0.05$) from 37.77% to 54.95% with a reduction in the pH value from 5.65 to 5.15, which lead to a significant increase in weight loss. pH and salt content have significantly influenced the shrinkage and weight loss of beef jerky dried in combined microwave-convection drying. Lowering pH and increasing salt increased the shrinkage and weight loss. Samples with 3.28% salt at pH 5.15 were showed the highest shrinkage and weight loss, whereas samples with 1.28% salt at pH 5.65 had the lowest losses in terms of weight and volume. The shrinkage of beef jerky processed in the smokehouse was reported as 73.7% (Unklesbay et al., 1999), which is higher than the shrinkage measured for the samples dried using combined microwave-convection drying in this study. Also, pH significantly influenced the yield of beef jerky processed in a smoke house (Unklesbay et al., 1999). The results from the literature support the current study.

The water activity of the different pH samples at 2.28 and 3.28% salt content were significantly different ($p < 0.05$) from each other, though there was no difference found between samples with pH 5.65 and 5.30 at 1.28% salt content. However, the water activities value of samples with 1.28% salt content and having pH 5.65 and 5.30 fell out of the safer range (≤ 8.5) recommended by USDA (2003). The products reached temperatures of 81.4 and 88.2°C, which would assure that all pathogens would be killed. The water activity of the samples varied from 0.82 to 0.77, when the pH was reduced from 5.65 to 5.15. Low pH samples had low water activities. While samples were at the same moisture content, they showed significantly different extents of shrinkage depending on formulation. For samples at pH 5.65, shrinkage increased from 32.14% to 48.32% with the addition of 1.28 to 3.28% salt. The effect of salt addition was found to be significant in shrinkage and water activity. Increase in salt content led to high shrinkage loss and low water activity.

The water activity of beef jerky sample was significantly influenced by salt content. It was reduced to 0.75 from 0.85 by the addition of 3.28% salt at pH 5.30. At pH 5.15, the effects of salt addition on water activity were not significant for the samples having 1.28 and 2.28 % salt. However, the samples with 3.28% salt showed significant reduction in water activity compared to other samples at pH 5.15. Lee and Kang (2003) did a study on ostrich jerky and reported that water activities measured for ostrich jerky dried under different temperatures, were within the range of 0.51 - 0.72 and the one prepared to 24% final moisture content at 70°C temperature had the highest water activity of 0.72. Similar water activity was measured for the jerky samples prepared with 3.28% salt content and lower pH levels. Another study revealed that ready-to-eat commercially available jerky type snack foods had less than 0.8 water activities due to a lower moisture content of 20% (Konieczny et al., 2004). Farouk and Swan (1999) reported that jerky processed from hot and cold boned meat and frozen and chilled stored meat had a water activity range of 0.72 - 0.75. However, the results obtained from combined microwave-convection drying showed a higher range of water activity (0.86 to 0.68).

Shrinkage, weight loss and water activities were significantly influenced by pH and salt content. Due to the rapid and high moisture removal rate of high salt and low pH samples, shrinkage and weight loss were increased.

4.1.5. Color parameter

The CIE color parameters of beef jerky samples prepared with different pH and salt content are presented in Table 4.5. The observations show that the lightness value has increased when the sample pH was altered from 5.65 to 5.30 and 5.15. Lower lightness values indicate that the samples were darker than others (Rahman et al., 2002). The lightness value of the jerky dried in combined microwave jerky were within the range of 25.95 to 36.25, which is similar to the L values of beef jerky (36.1 to 36.7) reported by Farouk and Swan (1999). The redness values were measured for beef jerky dried in combine microwave-convection drying as 12.48 to 21.44. These values are much higher than the reported value of 5.9 to 6.9 for jerky by Farouk and Swan (1999). Microwave-convection drying has increased the redness of the sample; this is based on the initial redness value of the raw jerky samples. The b* value was found to be in the range of 7.45 to 15.02, again this yellowness value were higher than the reported b* value of beef jerky of 2.8 to 3.3 (Farouk and Swan, 1999). Some other color values of jerky samples reported in literatures are also comparable with the results of this study. The Hunterlab color values (L, a and b) of beef jerky reported by Konieczny et al. (2007) were 30.66, 13.42 and 4.24, respectively. And Hunterlab color values L, a and b reported for ostrich jerky having 24% moisture content and dried at 70°C were 27.2 , 2.0 and 2.3, respectively (Lee and Kang, 2003). Coriander dried at combined mw drying method has shown a color index value of 2.67 (Shaw et al., 2007), which implies the color change found in beef jerky samples were significantly higher for beef jerky.

Table 4.5. CIE Color parameter of beef jerky samples dried under combined microwave-convection drying method.

pH	Salt Content (% (w/w))	L*	a*	b*	ΔE
5.65	1.28	25.95 ± 0.31 f	19.57 ± 0.25 b	11.51 ± 0.34 c	14.04 ± 0.08 a
	2.28	24.79 ± 0.51 g	14.08 ± 0.57 d e	7.56 ± 0.45 f	14.16 ± 0.56 a
	3.28	27.72 ± 0.07 e	15.82 ± 0.30 c	10.68 ± 0.45 d	13.86 ± 0.34 a
5.30	1.28	28.87 ± 0.43 d	12.48 ± 1.13 f	9.36 ± 0.20 e	11.75 ± 0.80 b
	2.28	25.31 ±0.88 g f	15.38 ± 0.29 c d	8.61 ± 0.01 e	9.74 ± 0.75 c
	3.28	33.71 ± 0.33 b	13.44 ± 0.52 e f	10.18 ± 0.12 d	4.50 ± 0.42 d e
5.15	1.28	30.30 ± 0.49 c	15.06 ± 0.48 c d	9.35 ± 0.43 e	3.50 ± 0.37 f
	2.28	28.54 ±0.22 d e	21.37 ± 0.65 a	12.75 ± 0.98 b	5.34 ± 0.22 d
	3.28	36.25 ±1.04 a	21.14 ± 1.58 a	15.01 ± 0.55 a	4.30 ± 0.37 e f

Means in the same column with different letters are significantly different ($p < 0.05$).

The effect of pH was statistically significant for lightness and a* values of the beef jerky samples dried with different salt content in combined microwave-convection drying. But, the difference in b* values between the samples with pH 5.30 and 5.15 at 1.28% salt content was not found to be significant. Also the redness value of samples with pH 5.65 and 5.30 at 3.28% salt content were not significantly different. Overall color change which is indicated by the color index significantly differed due to the pH alteration, though there was no difference found between low pH samples at 3.28% salt content in color change. The effect of amount of salt in the sample on lightness value was significant. However, the lightness value was found to be slightly high for samples with higher and lower salt content compared with 2.28% salt. At pH 5.65, color index was similar for all the samples.

The combined effect of pH and salt has influenced the color of the beef jerky. Samples with low pH (5.15) and high salt content (3.28%) had higher L*, a* and b* values compared to the others.

4.1.6. Textural characteristics

Mechanical properties of the samples dried in combined microwave-convection drying were measured and the effects of pH and salt content on those properties of the beef jerky were analyzed and the results are discussed in this section.

Different parameters measured in the puncture test for the samples having different pH and salt content are given in Table 4.6. The puncture forces measured were in the range of 30.87 N to 51.82 N. These values are considerably lower than the reported puncture values by other researchers. Lee and Kang (2003) have reported the puncture force required by intact ostrich jerky (24% wb) as 148.3 N. Also the puncture force of beef jerky commercially sold in Korea, was 128.9 N (Lee and Kang, 2003). Yet, the puncture force of formed beef jerky was 18.22 N (Texture Technology Corp., 2005), which is softer than the formed jerky samples dried in combined mw-convection drying.

Table 4.6. Puncture properties of beef jerky samples dried under combined microwave-convection drying

pH	Salt Content (% (w/w))	Force (N)	Area (N.s)	Gradient (N/s)
5.65	1.28	30.87 ± 1.63 d	184.97 ± 6.16 c	$0.0027 \pm 1.7 \times 10^{-4}$ g f
	2.28	43.59 ± 2.06 c	85.00 ± 3.18 e	$0.0074 \pm 2.2 \times 10^{-4}$ c
	3.28	51.82 ± 2.80 a	305.24 ± 13.56 a	$0.0029 \pm 3.7 \times 10^{-4}$ f
5.30	1.28	32.42 ± 1.33 d	216.92 ± 9.08 b	$0.0050 \pm 1.5 \times 10^{-4}$ e
	2.28	42.76 ± 1.76 c	152.70 ± 7.78 d	$0.0025 \pm 1.6 \times 10^{-4}$ g
	3.28	49.74 ± 2.06 a b	297.81 ± 12.08 a	$0.0050 \pm 2.7 \times 10^{-4}$ b
5.15	1.28	32.64 ± 1.85 d	174.18 ± 6.01 c	$0.0066 \pm 1.7 \times 10^{-4}$ d
	2.28	43.93 ± 1.97 c	311.54 ± 9.26 a	$0.0068 \pm 1.6 \times 10^{-4}$ d
	3.28	47.84 ± 1.99 b	213.15 ± 5.88 b	$0.0103 \pm 6.4 \times 10^{-4}$ a

Means in the same column with different letters are significantly different ($p < 0.05$).

The effect of pH on puncture force was not statistically ($P<0.05$) significant. But, the differences in the other puncture properties, total area and the slope of the force-time curve were statistically significant.

The forces required to penetrate through the jerky sample were measured as 30.87, 43.59 and 51.82 N for 1.28, 2.28 and 3.28% salt content at control pH samples. These were significantly different from each other. Addition of more salt highly influenced the puncture force and other parameters such as total area and slope. Samples with lower salt content showed a lower force to puncture the jerky, where the puncture test mechanically imitates the biting action. Puncture properties were also affected significantly by the amount of salt added at pH 5.30. Puncture force was found to be high for 3.28% salt content samples at pH 5.15. The force was increased linearly with the increase in amount of salt added. This shows the fact that the samples became harder with more salt. The samples dried at 1.28% salt content were the softest jerky dried in combined microwave-convection drying.

These effects of salt on texture of the beef jerky could be due to the binding of proteins occurred with the incorporation of salt in the meat. Toughening of myofibrils between the temperatures of 65°C and 75°C occurs due to the contracture of the collagen sheath and removal of moisture from myofibrils, which is caused by the temperature higher than 60°C (Sweat, 1986). There are also possibilities for cross-linking and hardening reactions and interaction of proteins due to the moisture loss during heating (Seideman and Durland, 1984). The myofibrillar proteins, extracted from the meat during sample preparation, helps in binding the ground meat to form the slices. These bondages between proteins greatly influence the texture of the final product. Addition of salt enhances the protein extraction. Due to the higher moisture removal rates in the samples with higher salt content, the hardening and protein binding became higher too.

The tensile test results of samples dried in combined microwave-convection drying are presented in Table 4.7.

Table 4.7. Tensile properties of beef jerky samples dried under combined microwave-convection drying.

pH	Salt Content (% (w/w))	Force (N)	Elongation(mm)	Energy (J)
5.65	1.28	31.10 ± 2.37 g	4.37 ± 0.19 b	$7.15\times10^{-2} \pm 2.8\times10^{-3}$ d
	2.28	61.90 ± 3.30 d	3.58 ± 0.23 c	$8.03\times10^{-2} \pm 2.2\times10^{-3}$ b
	3.28	62.70 ± 2.12 d	3.36 ± 0.24 d	$7.68\times10^{-2} \pm 1.4\times10^{-3}$ c
5.30	1.28	27.10 ± 1.43 g	5.76 ± 0.06 a	$6.86\times10^{-2} \pm 0.9\times10^{-3}$ d
	2.28	45.70 ± 3.54 e	3.06 ± 0.16 e	$8.54\times10^{-2} \pm 3.0\times10^{-3}$ a
	3.28	71.85 ± 3.08 c	2.48 ± 0.08 f	$1.22\times10^{-2} \pm 1.4\times10^{-3}$ g
5.15	1.28	36.55 ±1.78 f	2.00 ± 0.14 g	$1.67\times10^{-2} \pm 3.3\times10^{-3}$ f
	2.28	85.40 ± 2.16 b	1.73 ± 0.28 h	$3.31\times10^{-2} \pm 2.4\times10^{-3}$ e
	3.28	91.40 ± 2.92 a	1.46 ± 0.24 i	$7.93\times10^{-2} \pm 4.7\times10^{-3}$ b c

Means in the same column with different letters are significantly different ($p < 0.05$).

Tensile force of the dried jerky samples were found to be within the range of 31.10 N to 91.40 N. Compared to the tensile properties of beef jerky reported by different investigators, the tensile properties of jerky processed using combined microwave-convection drying had distinctly lower tensile properties. The samples dried in combined microwave-convection dryer had lower tensile force, energy and higher elongation than other reports. Tensile properties of whole muscle ostrich jerky (24% wb moisture content and 70°C) were reported as 261.3 N (tensile force), 2.5% (elongation) and 0.49 J (energy). And the values for beef jerky commercially sold in Korea were 218.6 N (tensile force), 5.8% (elongation) and 0.6 (energy) (Lee and Kang, 2003). Tensile strength of 88.51 N and elongation of 8.68 mm were reported for restructured beef jerky (Konieczny et al., 2007).

The samples with the lowest pH required more force to stretch the samples, which indicates that the stiffness of the product was increased with the acidity level. At 1.28% salt content, the difference in tensile force between higher pH levels was not significant. The samples having pH

5.30 and 1.28% salt had the highest elongation. Also, this treatment samples required less tensile force too. The tensile energy was also significantly affected by pH change. The pH 5.15 samples had more tensile force with less displacement, which indicates the sample have lower elasticity than other two treatments. The energy required to pull the samples were found to differ significantly. At 3.28% salt content also, the effect of pH found on tensile properties, showed that lower pH sample possessed higher tensile force and lower displacement value. This indicates that pH 5.15 samples were tougher than higher pH samples. Hardening of high acid products can be explained by the faster moisture removal taking place during drying. Protein denaturation occurs at high temperatures, where the product temperature of lower pH samples reached higher temperature than others.

The tensile properties of the beef jerky were significantly influenced by the amount of salt added. Tensile force was observed as 31.10 N with elongation of 4.37mm for 1.28% salt and 62.70 N with 3.35 mm of elongation for 3.28% salt. Samples with 2.28% salt required higher energy than the samples with 1.28 and 3.28% salt to stretch the jerky samples. From the results, it can be understood that the higher amount of salt resulted in hardening the product. Tensile properties also have been significantly influenced by the amount of salt added. Tensile force increased significantly when the salt was increased to 3.28% from 1.28%. The displacement values were reduced, which indicates that the sample with 3.28% salt got stiffer compared to lower salt content samples. Hardening of the high salt content samples can be explained; a higher product temperature was reached while drying and a higher drying rate was observed at high salt content samples. These factors lead to higher shrinkage and hardening of myofibril. Also, the protein which binds the myofibrils together influences the textural properties. More salt binds more with protein and resulting in a tougher end product.

Sample pH and salt have significantly influenced the tensile properties of jerky. Samples with lower pH (5.15) and higher salt (3.28%) have produced harder beef jerky having the highest tensile force and the lowest elongation.

Different texture parameters found using the texture profile analysis (TPA) are given in Table 4.8 and Table 4.9. The hardness values of the combined microwave-convection dried beef jerky samples were in the range between 46.97 N and 65.20 N.

Table 4.8. Texture profile analysis results of beef jerky samples dried under combined microwave-convection drying.

pH	Salt Content (% (w/w))	Hardness (N)	Cohesiveness	Gumminess (N)
5.65	1.28	35.89 ± 4.53 e	0.76 ± 0.32 b	26.85 ± 2.38 b
	2.28	54.79 ± 2.85 c	0.71 ± 0.02 c	37.86 ± 2.83 a
	3.28	65.94 ± 2.93 a	0.62 ± 0.02 d	40.79 ± 2.20 a
5.30	1.28	49.33 ± 2.52 d	0.76 ± 0.00 b	38.42 ± 3.20 a
	2.28	52.98 ± 2.79 c	0.75 ± 0.01 b	39.90 ± 0.42 a
	3.28	58.74 ± 1.58 b	0.76 ± 0.02 b	40.61 ± 0.81 a
5.15	1.28	26.97 ± 2.67 f	0.39 ± 0.01 e	12.04 ± 2.44 c
	2.28	48.75 ± 0.89 d	0.81 ± 0.02 a	39.62 ± 1.44 a
	3.28	65.20 ± 1.83 a	0.38 ± 0.01 e	26.21 ± 1.25 b

Means in the same column with different letters are significantly different ($p < 0.05$).

It was found that pH and salt have significantly influenced the TPA textural parameters. The influence of pH on hardness and chewiness values weren't linear. Samples with 3.28% salt content and pH 5.15 and 5.65 were found to be harder than others. Differences found among cohesiveness and resilience values of the samples with different pH were significant. Overall effect of pH on springiness value was not significant. Samples with lower pH (5.15) at 1.28% salt content had the lowest hardness, cohesiveness, gumminess, springiness and chewiness values with highest resilience value. This indicates that this combination produced softest jerky.

Table 4.9. Texture profile analysis results of beef jerky samples dried under combined microwave-convection drying.

pH	Salt Content (% (w/w))	Resilience	Springiness	Chewiness (N)
5.65	1.28	0.56 ± 0.01 c	0.81 ± 0.01 b c	20.02 ± 1.55 c
	2.28	0.33 ± 0.02 f	0.86 ± 0.02 a	33.98 ± 1.34 a
	3.28	0.25 ± 0.03 g	0.81 ± 0.04 b c	29.47 ± 1.36 b
5.30	1.28	0.57 ± 0.01 b c	0.82 ± 0.02 a b c	31.28 ± 0.75 b
	2.28	0.59 ± 0.01 b	0.85 ± 0.03 a b	33.39 ± 1.21 a
	3.28	0.60 ± 0.01 b	0.85 ± 0.02 a	34.84 ± 1.26 a
5.15	1.28	0.73 ± 0.03 a	0.71 ± 0.01 d	15.69 ± 1.10 d
	2.28	0.52 ± 0.01 d	0.86 ± 0.01 a	34.58 ± 1.62 a
	3.28	0.48 ± 0.01 e	0.78 ± 0.01 c	20.65 ± 1.04 c

Means in the same column with different letters are significantly different ($p < 0.05$).

The significant differences found in the textural parameters presented above indicate that the higher salt content samples had the highest hardness and gumminess values. The chewiness was significantly increased from 1.28% to 3.28% salt samples, though the effect found between 2.28 and 3.28% were not always significant at pH 5.30. The salt content didn't have any significant effect in textural properties such as cohesiveness, gumminess, resilience and springiness at pH 5.30. An increase in salt content resulted in significantly hard samples.

Hardening of the product might have occurred due to the cross-linkages and protein binding which occurred while drying. Due to the higher shrinkage, the myofibrils were cross-linked and became tougher. Samples with 2.28% salt content had the highest chewiness value. Samples having pH 5.15 and 1.28% salt content had the lowest hardness value (26.97 N) and softer in texture.

In summary, salt content significantly influenced the textural properties of beef jerky. Mainly, 3.28% salt content samples found to be harder than the lower salt jerky sample. Combined effect of pH and salt significantly affected the textural characteristics of beef jerky. Samples with low pH and high salt have produced softer jerky and samples with high pH and low salt were tough.

4.1.7. Summary

In summary, the observations revealed that pH and salt content had a significant influence in drying characteristics of beef jerky dried in combined microwave-convection drying. Drying rate was found to be high in lower pH samples. Increasing the salt content increased the drying rate and reduced the drying time. It was observed that samples with the combination of 3.28% salt and pH 5.15 had the highest drying rate (19.5 kg of water per kg of dry matter per h) and as the result it has the lowest drying time (5.5 min). When the physical-chemical characteristics were examined, it was revealed that both pH and salt content had significantly influenced the volume and weight loss; and water activity. The high pH samples have had the high losses and the highest water activities. Samples with pH 5.65 and 1.28% salt content had the low weight loss and shrinkage. The water activities were within the range of 0.86 to 0.68. Low pH samples had a darker color than others and samples with 2.28% salt content had darker color than the rest of the salt added samples. Overall, the color change was significant with pH change, but not with salt content change. Puncture force was not significantly influenced by pH, but by salt content. Combination of 1.28% salt content and pH 5.65 treatment had the softer textural characteristics (Puncture force 30.87 N; tensile force 31.10 N; hardness 35.890 N). Overall, jerky with lower pH and higher salt content had the better drying characteristics. However, it was observed that jerky at pH 5.65 (control) and 1.28% salt content had lower losses in terms of weight and dimension. Also, this treatment combination had produced softer jerky.

4.2. Effect of Relative Humidity and Airflow Rate on Thin-Layer Drying

In this section, experimental results obtained using forced-air thin-layer drying experiments are presented. The effect of relative humidity and airflow rate of the air (drying medium) in thin-layer drying was investigated and the effect on different properties of beef jerky is presented in the following section. The beef jerky was formulated to contain 2% salt and was at pH 5.65.

4.2.1. Drying characteristics

Table 4.10 exhibits the drying characteristics (drying rate and drying time) of beef jerky dried in a forced air thin layer drying unit. The statistical analysis revealed that there was a significant difference in these drying parameters. Drying rate and drying time of the samples dried under different airflow rate varied significantly. Increasing the airflow rate from 1 to 1.45 m/s, have improved the process, thus reducing the drying time. Samples dried with 40% relative humidity and 1.45 m/s airflow rate had a drying rate of 0.51 kg of water per kg of dry matter per h, which was significantly faster than the drying rate of the samples dried with 1 m/s air with the same relative humidity (0.34 kg of water per kg of dry matter per h). The same trend was found in other studies done on the thin layer drying of plant materials. Stamatios et al. (2005) have found that air velocity was a significant factor when drying figs. At the beginning of the drying process, higher airflow rate accelerates the drying process by improving surface evaporation. The drying curves in Figure 4.15 and 4.16 show the effect of airflow rate at 40 and 15% relative humidities. As the surface evaporation was accelerated, the drying curve of the samples dried at 1.45 m/s air velocity has a shorter constant rate period, when the free moisture evaporate from the surface and at the same time moisture from the centre migrates to the surface. The drying constants were also influenced by airflow rate change (Table 4.11). The *K* value increased with the increase in the airflow rate.

Table 4.10. Drying characteristics of beef jerky samples dried under forced-air thin layer drying unit.

RH (%)	Airflow Rate (m/s)	Drying Time (h)	Average Drying Rate (kg of water per kg of dry matter per h)
40	1.00	7.02 ± 0.19 a	0.34 ± 0.011 d
	1.45	4.47 ± 0.20 b	0.51 ± 0.003 c
15	1.00	4.25 ± 0.05 b	0.55 ± 0.002 b
	1.45	2.97 ± 0.06 c	0.78 ± 0.002 a

Means in the same column with different letters are significantly different ($p < 0.05$).

Table 4.11. Drying constants and models of beef jerky samples dried using thin-layer drying method.

RH (%)	Airflow Rate (m/s)	R^2	Std. Error	Drying Constants (K in min^{-1})
40	1.00	0.999	0.003	K=0.2152; n= 1.2867
	1.45	0.999	0.004	K=0.4914; n=1.2297
15	1.00	0.999	0.008	K=0.4999; n=1.1908
	1.45	0.999	0.001	K=0.8005; n=1.1587

The drying rate was significantly increased when the relative humidity of the air was reduced from 40% to 15%, which accelerated the drying process and it took 4.25 h to dry to the final moisture content 0.33 dry basis rather than 7.02 h (Table 4.10). The effect of relative humidity on drying rate and drying time was statistically significant, even when the airflow rate was changed to 1.45 m/s. In both cases, the drying rate and drying time were increased with reduced relative humidity. As the air gets dry, the diffusivity increases. Apparently, this results in a higher drying rate. The drying data were fitted to different drying models and it was found that Page's model fitted well. The highest drying rate and lowest drying time were observed for the samples dried with 1.45 m/s air velocity and 15% relative humidity. The drying constant for this sample was determined as 0.8 min^{-1} and the exponent as 1.15.

The drying curves obtained for jerky samples dried in the thin-layer convection drying unit with 1 m/s airflow rate are shown in Figure 4.13. At the beginning of drying, the moisture removal rate was increased to its highest level and a constant rate was maintained for two hours in the samples dried at 40% relative humidity and 1 m/s airflow. This drying behavior indicates that the surface moisture removal was moderate at this relative humidity compared with the one dried at 15% relative humidity. At low relative humidity, the moisture transfer between hot air and the product was high due to the higher diffusion rate and the potential difference between the medium and product surface moisture. As a result of this, the free water evaporated faster thus ending its constant rate period fast compared with the high relative humidity. As the potential difference in moisture transfer between air and moisture from the interior of the product was reduced as compared to the first stage of drying, a falling rate period was followed by the constant rate period. As in the low relative humidity samples, there was no constant rate period found. After the first 30 mins of the drying, the sub surface moisture was removed during a falling rate period.

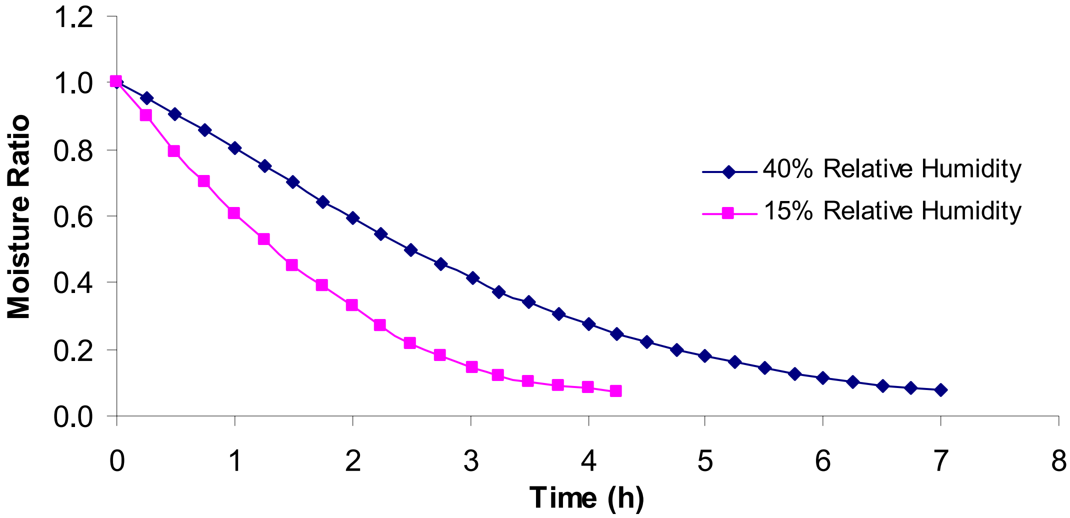

Figure 4.13. Drying curves of beef jerky dried in a thin-layer convection dryer showing the effect of relative humidity at the air flow rate of 1.00m/s.

At 1.45 m/s airflow rate, both samples dried with 40 and 15% relative humidity have behaved similarly, due to the effect of airflow rate. At higher airflow rate, the moisture removal was accelerated due to the faster air movement. So, the combined effect of relative humidity and airflow rate left the drying behavior of the beef jerky unchanged. However, the moisture removal rate was found to be higher for samples dried at 15% relative humidity. Both samples had a constant rate period for 1.5 h (40% RH) and 1 h (15% RH) at the beginning of the drying process and later the moisture removal from subsurface was carried out at the successive falling rate periods.

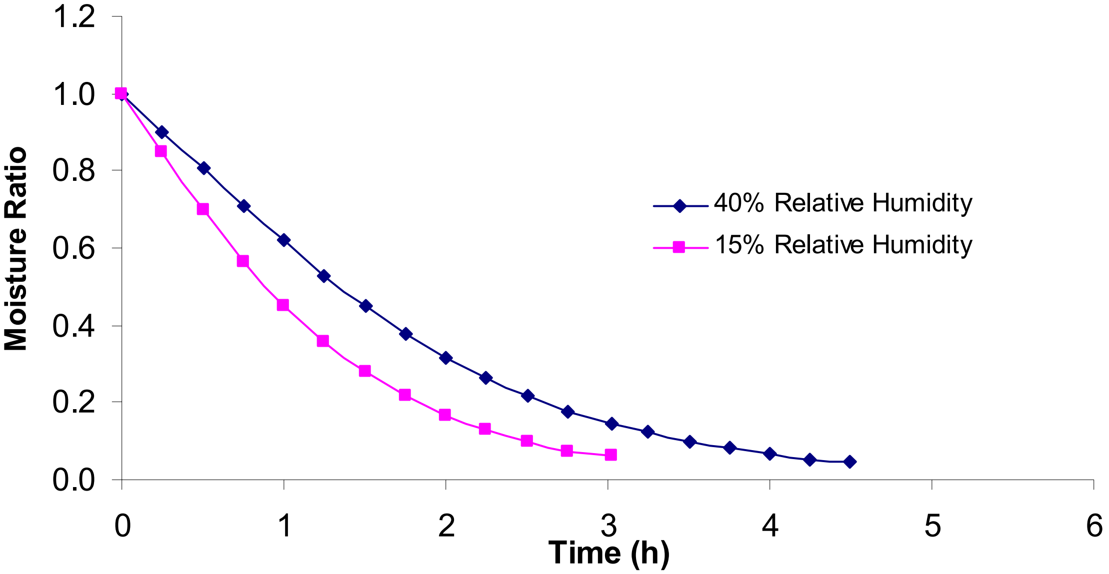

Figure 4.14. Drying curves of beef jerky dried in a thin-layer convection dryer showing the effect of relative humidity at the air flow rate of 1.45m/s.

Drying curves of beef jerky observed for different airflow rate at 40% relative humidity are shown in Figure 4.15. The jerky had a longer constant rate period for samples dried at lower airflow rate, where the drying behavior found for samples dried at lower humidity had a constant rate period at the beginning, where the free water was evaporated quicker because of the faster air movement. This improved the drying rate of the samples at the beginning of the drying stage. A falling rate period occurred following by the constant rate periods after 2 and 1.5 h at 1 and 1.45 m/s airflow rate, respectively. The faster moisture removal at the first stage of drying at higher airflow rate resulted in reduced drying time as previously shown in Table 4.10.

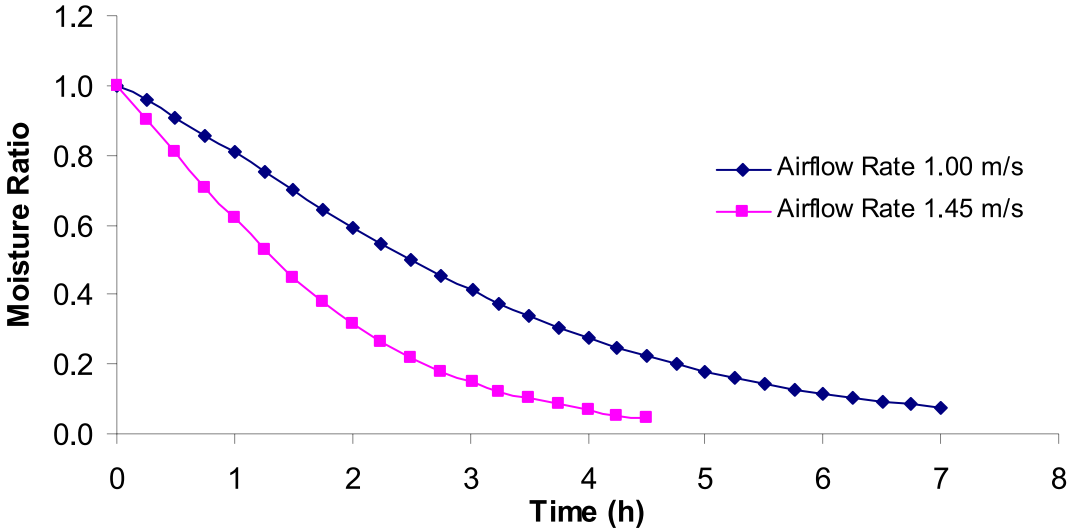

Figure 4.15. Drying curves of beef jerky dried in thin layer convection dryer showing the effect of airflow rate at 40%relative humidity.

The drying curves shown in Figure 4.16 were drawn for beef jerky samples dried at 15% relative humidity in a thin-layer forced air convection dryer. At 15% relative humidity, samples dried at 1 m/s airflow rate did not have a constant rate and the drying was carried out during a falling rate period. The combined effect of lower relative humidity and higher airflow rate caused a higher drying rate which lead to reduced drying time.

The combined effect of lower relative humidity and higher airflow rate helped to dry the beef jerky samples faster by improving their drying rate. Lower relative humidity and higher airflow rate have shown increased drying rate and reduced drying time. A relative humidity of 15% and airflow rate of 1.45m/s had the potential to reduce the drying time of beef jerky in thin layer drying unit to 3 h.

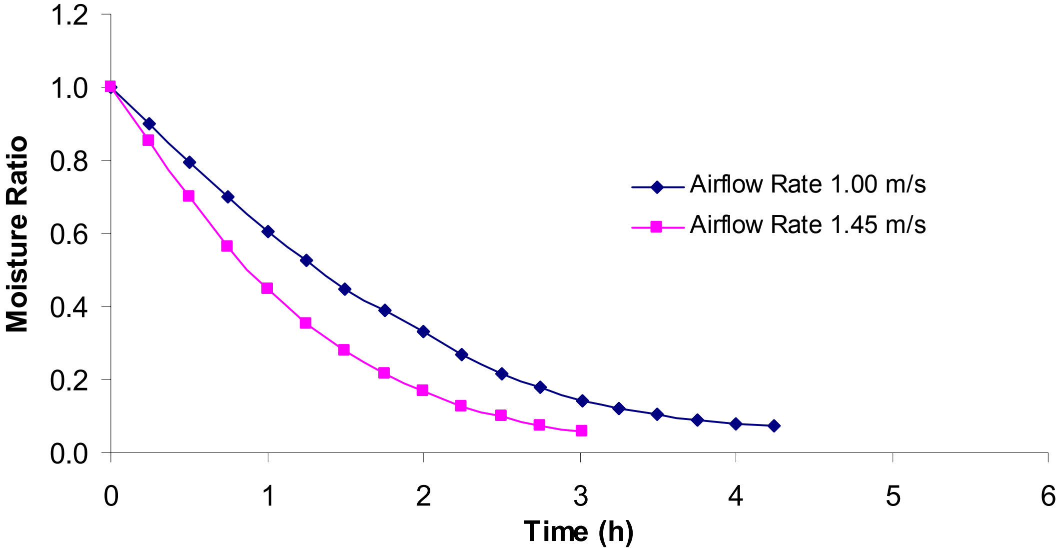

Figure 4.16. Drying curves of beef jerky dried in thin-layer convection dryer showing the effect of airflow rate at 15% relative humidity.

4.2.2. Physical-chemical characteristics

Table 4.12 shows the effect of relative humidity and airflow rate on weight loss, shrinkage and water activity of beef jerky. The shrinkage loss of beef jerky dried in a thin-layer drier was significantly increased when the relative humidity was reduced from 40% to 15%. Reducing the relative humidity lowered the water activity from 0.780 to 0.66 in samples dried at 1 m/s, whereas it was reduced from 0.74 to 0.63 in samples dried at 1.45 m/s. There was a significant difference found in the shrinkage loss, weight loss and water activity values for samples dried at 40% relative humidity with different airflow rate.

The lowest shrinkage and weight loss were measured for the samples dried at high relative humidity (40%) and low airflow rate (1 m/s), thereby suggesting that accelerated moisture diffusion increased the shrinkage and weight loss under lower relative humidity and higher airflow rate conditions. At the higher airflow rate, the evaporation from the surface was very high compared to samples dried with lower airflow at the initial stages of drying. So, the moisture transfer from the centre of the product to the surface was also hastened. Thus, there was an increase in the loss in weight as well in shrinkage.

Table 4.12 Physical-chemical properties of beef jerky samples dried under forced-air thin-layer dryer.

RH (%)	Airflow Rate (m/s)	Shrinkage (%)	Weight Loss (%)	Water Activity
40	1.00	41.17 ± 1.14 d	62.57 ± 0.09 c	0.80 ± 0.003 a
	1.45	49.31 ± 1.48 c	62.74 ± 0.06 b	0.74 ± 0.007 b
15	1.00	58.51 ± 1.34 b	62.90 ± 0.07 b	0.65 ± 0.004 c
	1.45	60.43 ± 0.22 a	63.72 ± 0.06 a	0.63 ± 0.006 d

Means in the same column with different letters are significantly different ($p < 0.05$).

Water activities of the beef jerky samples dried at different relative humidity and airflow rate were within the range of 0.80 to 0.63. Water activities of the samples are significantly reduced, when the airflow rate was increased from 1 m/s to 1.45 m/s. Water activity was also significantly influenced by relative humidity of the heating medium and the air flow rate. The results suggest that at low relative humidity the moisture removal was faster and this caused the water activity to drop to a low value. These values were within the range of USDA (2003) standards for safety. As well similar water activity values were measured for jerky in other studies (Farouk and Swan, 1999; Lee and Kang, 2003).

Physical and chemical characteristics such as weight loss, shrinkage loss and water activities were significantly influenced by relative humidity and airflow rate. The combined effect of these factors showed that low relative humidity and high airflow rate will lead to high losses in terms of weight and volume.

4.2.3. Color parameters

The CIE color parameters measured for the samples dried at two different relative humidities and two different airflow rates in the forced air thin layer drying unit are tabulated in Table 4.13.

Table 4.13. Color parameters of beef jerky samples dried using forced-air thin layer dryer.

RH (%)	Airflow Rate (m/s)	L*	a*	b*	ΔE
40	1.00	18.64± 0.09 d	10.38 ± 0.17 a	9.47 ± 0.19 a	17.43 ± 0.16 a
	1.45	20.95± 0.83 c	5.27 ± 0.33 b	4.56 ± 0.13 d	16.97 ± 0.17 b
15	1.00	25.59± 0.08 b	5.28 ± 0.01 b	8.57 ± 0.12 b	10.74 ± 0.12 c
	1.45	29.11± 0.03 a	4.79 ± 0.08 c	6.98 ± 0.03 c	8.92 ± 0.05 d

Means in the same column with different letters are significantly different ($p < 0.05$).

The Duncan mean difference test done on these data showed that the color values were significantly changed when different relative humidities and airflow rates were used to dry the jerky samples. The lightness value increased when the relative humidity was reduced from 40% to 15% and when the air velocity was increased (Table 4.13). Farouk and Swan (1999) reported that lightness values of jerky prepared from meat samples processed and stored differently ranged between 36.1 and 36.7, a* values varied from 5.9 to 6.9, and b* values ranged between 2.8 and 3.3. The sample dried with 15% relative humidity and 1.45 m/s air velocity was the closest in L value to that obtained by Farouk and Swan (1999). Another kind of jerky prepared by Konieczny et al. (2007) had Hunterlab color values of 30.66, 13.42 and 4.24 (L, a and b), respectively. The Hunterlab color values L, a and b reported for ostrich jerky having 24% moisture content and dried at 70°C were 27.2 , 2.0 and 2.3, respectively, (Lee and Kang, 2003). The redness value was reduced at the low relative humidity and high airflow rate. The color values measured were not completely comparable with the previously reported data [Lee and Kang (2003); Farouk and Swan (1999) and Konieczny et al. (2007)] due to the different composition of the sample formulations used to prepare the jerky.

The experimental results show that the color values of the beef jerky samples dried in a thin-layer dryer were significantly influenced by relative humidity and airflow rate.

4.2.4. Textural characteristics

The mechanical properties of jerky processed in thin layer drying unit are measured and displayed in Tables 4.14 to 4.17.

Table 4.14. Puncture properties of beef jerky samples dried using forced-air thin layer dryer.

R.H. (%)	Airflow Rate (m/s)	Force (N)	Area (N.s)	Gradient (N/s)
40	1.00	16.77 ± 0.66 d	63.02 ± 2.39 c	0.0054 ± $2\text{x}10^{-4}$ c
	1.45	26.77 ± 0.95 c	65.44 ± 0.13 c	0.0055 ± $1\text{x}10^{-4}$ c
15	1.00	33.93 ± 2.93 b	108.60 ± 1.31 b	0.0092 ± $3\text{x}10^{-4}$ a
	1.45	42.84 ± 2.48 a	135.90 ± 1.18 a	0.0076 ± $2\text{x}10^{-4}$ b

Means in the same column with different letters are significantly different ($p < 0.05$).

The puncture test results are shown in Table 4.14. The puncture force values were between 16.77 to 42.84 N. The puncture force reported for formed beef jerky by Texture Technologies Corporation was 18.22 N (Texture Technology Corp., 2005). Puncture force of beef jerky commercially sold in Korea, was reported as 128.9 N (Lee and Kang, 2003). Lee and Kang (2003) have also reported that whole muscle ostrich jerky dried at 70°C required 148.3 N to penetrate through. Comparing with these data, the jerky dried in thin layer drying unit have required much lesser force to puncture (16.77 to 42.84 N).

It was found that there was a significant effect of relative humidity and airflow rate during thin layer drying on puncture force. Other properties such as area and gradient of the curve derived also were influenced by the change in relative humidity, though there was no significant difference found between samples dried at 40% relative humidity on these parameters. The area and slope of the curve reported for beef jerky was 145.64 N. s and 2.07 N/s (Texture Technologies Corp., 2005). The puncture force of the jerky was increased from 16.77 N to 33.93

N when the relative humidity was changed from 40% to 15% at 1 m/s air velocity. This indicates that the sample became harder when the relative humidity was reduced to 15%. Samples also became harder when the airflow rate was increased. It can be explained by the drying behavior of the jerky in the thin layer convection air drying environment. The increased airflow rate and reduced relative humidity have tremendously increased the drying rate and thus induced faster moisture movement from the surface as well as within the product. This in turn, resulted in higher shrinkage and weight loss. Eventually, this faster moisture removal caused stiffening of the final product.

Table 4.15 shows the tensile properties of beef jerky dried in the thin layer convection dryer. It is clear from the table that tensile properties, tensile force, elongation and energy required were significantly influenced by relative humidity and airflow rate of the heating medium. The measured tensile force values ranged from 101.7 N to 184.6 N. Tensile properties of ostrich jerky (24% moisture content and 70°C) were reported as 261.3 N (tensile force), 2.5% (elongation) and 0.49 J (energy). And properties of beef jerky commercially sold in Korea were 218.6 N (tensile force), 5.8% (elongation) and 0.6 (energy) (Lee and Kang, 2003). Tensile strength of 88.51 N and elongation of 8.68 mm were reported for beef jerky (Konieczny et al., 2007). Tensile forces of the samples dried in the thin layer dryer were lower when compared with the previously reported tensile properties of jerky. This may be because the sample became harder while drying due to high airflow rate and low relative humidity and therefore these samples have possessed high tensile properties than the others.

Table 4.15. Tensile properties of beef jerky samples dried in a forced-air thin layer dryer.

RH (%)	Airflow Rate (m/s)	Force (N)	Elongation (mm)	Energy (J)
40	1.00	101.70 ± 4.03 d	2.83 ± 0.16 a	0.17 ± 0.01 d
	1.45	152.03 ± 2.04 c	2.39 ± 0.15 b	0.21 ± 0.01 c
15	1.00	174.07 ± 1.91 b	1.97 ± 0.01 c	0.24 ± 0.00 b
	1.45	184.60 ± 4.71 a	1.17 ± 0.02 d	0.28 ± 0.01 a

Means followed by different letters within each column are significantly different at $p<0.05$ levels according to Duncan’s multiple range Test.

The results of texture profile analysis obtained for jerky dried at two different relative humidities and two different airflow rates are tabulated in Tables 4.16 and 4.17.

Table 4.16. Texture profile analysis results of beef jerky samples dried in forced-air thin layer drying unit.

RH (%)	Airflow Rate (m/s)	Hardness (N)	Cohesiveness	Gumminess (N)
40	1.00	13.99 ± 0.81 d	0.89 ± 0.01 a	12.29 ± 0.67 d
	1.45	26.28 ± 0.48 c	0.81± 0.03 c	21.22 ± 0.54 c
15	1.00	31.76 ± 1.52 b	0.84 ± 0.04 b c	25.47 ± 0.70 b
	1.45	85.84 ± 1.87 a	0.87 ± 0.02 a b	74.00 ± 3.57 a

Means in the same column with different alphabets are significantly different ($p < 0.05$).

Table 4.17. Texture profile analysis results of beef jerky samples dried in a forced-air thin layer drying unit.

RH (%)	Airflow Rate (m/s)	Resilience	Springiness	Chewiness (N)
40	1.00	0.66 ± 0.02 a	0.89 ± 0.01 a	11.08 ± 0.40 d
	1.45	0.45 ± 0.03 b	0.82 ± 0.03 b	17.15 ± 0.73 c
15	1.00	0.62 ± 0.00 a	0.89 ± 0.04 a	22.98 ± 0.73 b
	1.45	0.64 ± 0.03 a	0.86 ± 0.01 a b	63.74 ± 2.79a

Means in the same column with different alphabets are significantly different ($p < 0.05$).

It was found that the sample became harder when the relative humidity was reduced and airflow rate was increased (Table 4.16). Hardness and chewiness values measured for freeze dried beef cubes have shown that these texture parameters were low for water activity more than 0.8 and high at the water activity range of 0.4 to 0.6 (Reidy and Heldman, 1972). This was also found to be true in this case, as the sample having the water activity of 0.80 had the lowest hardness and chewiness values (13.99 N and 11.08) and the hardness value was increased for the samples having the water activity of 0.65 and 0.63 (Table 4.12). Other texture parameters such as cohesiveness, gumminess and chewiness were significantly influenced by relative humidity and airflow rate (Tables 4.16 and 4.17). However, there was no significant difference found in springiness and resilience values. Basically, the hardness, chewiness and gumminess values increased with the rise in airflow rate and fall in relative humidity. It can be explained by the quicker moisture removal.

The combined effect of relative humidity and airflow rate in the textural characteristics of beef jerky dried in a thin layer drying unit were significant. Samples processed at low airflow rate and high relative humidity were softer compared to other samples.

4.2.5. Summary

From the observations made from the thin layer drying experiment, the effect of relative humidity and airflow rate significantly affected the forced air thin layer drying characteristics of beef jerky. Samples dried at relative humidity of 15% and airflow rate of 1.45 m/s showed better drying characteristics. Physical-chemical properties such as shrinkage, weight loss, water activity and color were found to be influenced by the relative humidity and airflow rate. Jerky dried by a combination of 40% relative humidity and 1 m/s air flow rate had low weight and shrinkage losses compared to others. Textural characteristic of the samples measured revealed that drying with 40% relative humidity hot air and 1 m/s airflow rate produced softer products than the rest of the treatments (Puncture force 16.77 N; tensile force 101.7 N; hardness 13.993 N).

4.3. Smoke Housing Processing

Different properties of the jerky samples with 2.28% (w/w) salt and pH 5.65, dried in a batch type smokehouse are displayed in the following section.

4.3.1. Drying characteristics

The drying data of the jerky processed in the smokehouse were fitted with different drying models and Page's model was found to be the best drying model in this case. The equilibrium moisture content was 0.179 db and drying constants K and n were calculated as 0.499 min^{-1} and 0.866. The drying rate curve is shown in Figure 4.17. The moisture removal at the first stage of the drying process was high and at this period free water from the surface was evaporated due to conduction. This period continued until the rate of evaporation of water from the surface was equal to the migration rate of water to the surface from interior. But, there is no constant rate period observed for jerky processed in a smoke-house. After this jerky had a first falling rate period in which most of surface moisture has already evaporated and unbound water molecules try to migrate to the air. This period lasted until the surface moisture becomes zero and at the end of the first falling rate, a second falling rate period of jerky was detected and at this period subsurface moisture removal takes place until it reached the equilibrium moisture content. The average drying rate of this process was calculated as 0.30 kg of water per kg of dry matter per h and average time it has taken was 6.88 h (Table 4.18). This value was slightly shorter than one reported in the literature. It took 9 h to dry Kilishi, a Nigerian dried meat product in sun drying (Egbunike and Okubanjo, 1999).

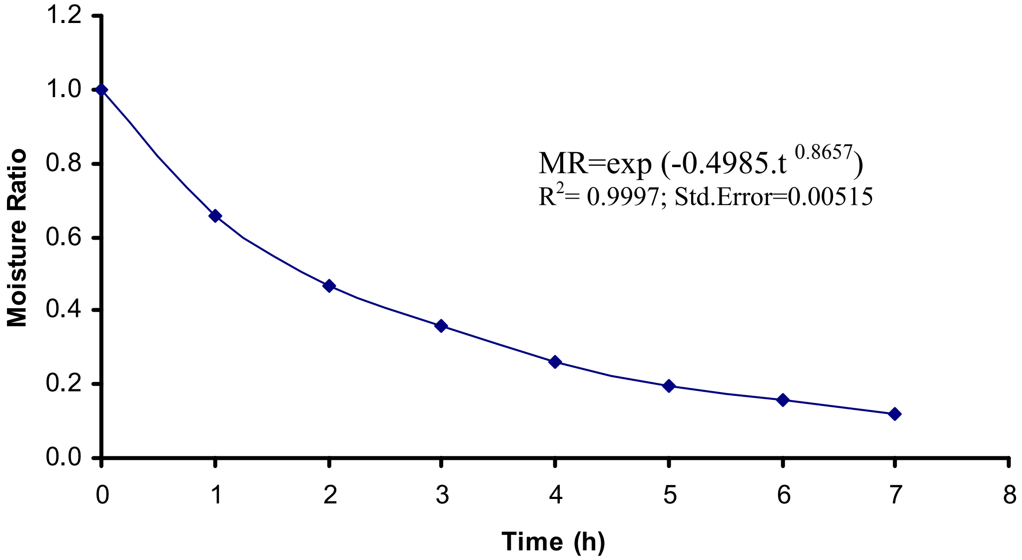

Figure 4.17. Drying curve of beef jerky processed in a smokehouse

Table 4.18. Drying characteristics of beef jerky samples prepared under smokehouse processing.

Properties	Mean	SD	CV (%)
Time Taken (h)	6.88	0.17	2.57
Average Drying Rate (kg of water per kg of dry matter per h)	0.30	0.05	17.20

4.3.2. Physical and chemical characteristics

Water activity of the beef jerky sample dried in a smoke-house was observed as 0.71, which is under the food safety recommendation by USDA (2003). This sample had a 52.6% shrinkage loss and 57.9% weight loss. These values are lower than the one reported in literature (Unklesbay et al., 1999). Unklesbay et al. (1999) reported that beef jerky processed in the smoke house had 73.7% shrinkage loss. The physical-chemical characteristics of beef jerky dried in a smoke-house are shown in Table 4.19.

Table 4.19. Physical-chemical characteristics of beef jerky processed in a smokehouse

Properties	Mean	SD	CV (%)
Shrinkage (%)	52.61	4.02	7.64
Weight Loss (%)	57.92	0.56	0.97
Water Activity	0.71	0.02	2.68

4.3.3. Color parameters

CIE color lab values of beef jerky dried in a smoke house are presented in Table 4.32. CIE color values for beef jerky: lightness = 36.1, a* = 5.9 and b* = 2.8 (Farouk and Swan, 1999). Hunterlab color values, L, a and b, reported for ostrich jerky having 24% moisture content and dried at 70°C were 27.2 , 2.0 and 2.3, respectively (Lee and Kang, 2003). The variation in the color values might be due to the different compositions of sample formulations. The color index, which shows the effect of drying on the sample, was found to be 6.878.

Table 4.20. Color parameters of beef jerky samples processed in a smoke house.

Properties	Mean	SD	CV (%)
L*	28.79	0.18	0.64
a*	7.64	0.22	2.91
b*	10.89	0.17	1.52
ΔE	6.878	0.09	1.27

4.3.4. Textural properties

Mechanical properties of the jerky samples dried in a smokehouse are presented in Tables 4.21-4.23. The measured puncture properties shown in Table 4.21, are higher than the ones reported by Texture Technology Corp. (2005) ie, 18.22 N, 145.64 N.s and 2.07 N/s.

Table 4.21. Puncture properties of beef jerky samples processed in a smoke-house.

Properties	Mean	SD	CV (%)
Force (N)	57.92	2.21	3.81
Area (N.s)	260.23	6.457	2.48
Gradient (N/s)	0.029	0.0005	1.77

Tensile properties measured for beef jerky samples dried in a smokehouse are displayed in Table 4.22. The tensile force value was within the range reported from previous study on jerky (Lee and Kang, 2003). Tensile properties of ostrich jerky (24% moisture content and 70°C) was reported as 261.3 N (tensile force), 2.5% (elongation) and 0.49 J (tensile energy). For beef jerky commercially sold in Korea was 218.6 N (tensile force), 5.8% (elongation) and 0.6 (tensile energy) (Lee and Kang, 2003).

Table 4.22.Tensile properties of beef jerky samples processed in a smoke-house.

Properties	Mean	SD	CV (%)
Force (N)	176.7	2.59	1.47
Elongation (mm)	1.77	0.03	1.43
Energy req. to break (J)	0.263	0.006	2.11

Results of texture profile analysis are presented in Table 4.23. The hardness and chewiness value was measured as 26.39 N and 12.77 N. These values were within the range of beef jerky processed in thin layer convection drying unit.

Table 4.23.Texture profile analysis results of beef jerky samples processed in a smoke-house.

Properties	Mean	SD	CV (%)
Hardness (N)	26.39	1.81	6.90
Cohesiveness	0.83	0.02	1.82
Gumminess (N)	13.58	1.20	8.85
Resilience	0.52	0.01	2.74
Springiness	0.86	0.01	1.51
Chewiness (N)	12.77	0.47	3.65

4.4. Comparison of Drying Methods

In this section, evaluation of the different drying methods such as hybrid microwave-convection drying, forced-air convection thin layer drying and smoke house drying in beef jerky processing was performed. Samples having the same initial parameters and prepared with same composition were compared and discussed.

Initial sample condition:

Initial moisture content: 70.94 ± 2.27% kg of water per kg of material

Sample pH : 5.65

Salt content : 2.28 % (w/w)

Processing condition:

Combined microwave-convection: 295 W, 70°C, 1.45 m/s air flow rate, 0% relative humidity

Forced air thin layer : 80°C, 1.45 m/s airflow rate, 15% relative humidity

Smoke house processing:

Table 4.24. Processing cycle used in smoke-house processing.

Air Temperature, °C	Relative humidity, %	Cycle Time, min
40	30	20
55	30	20
60	30	20
65	45	20
70	40	20
76	45	30 (Steaming)
50	25	Till end

Physical-chemical, drying and textural characteristics measured for the samples dried in different methods are displayed in Table 4.25. Drying characteristics such as drying rate and drying time show a significant difference among drying methods. The traditional smoke-house processing took 7 h to dry the samples to the 0.33 db final moisture content with an average drying rate of 0.297 kg of water per kg of dry matter per h.

Table 4.25. Different characteristics of beef jerky processed under different drying methods.

Characteristics	Hybrid microwave-convection drying	Forced-air thin layer drying	Smoke house processing
Drying Characteristics			
Drying Rate (kg of water per kg of dry matter per h)	16.360	0.778	0.297
Drying Time	8.25 min	3 h	7 h
Drying Constants (K in min^{-1})	K=0.1912; n=1.0417	K=0.8005; n=1.1587	K=0.4985; n=0.8657
Product Temperature	86.1°C	79.9°C	72.0°C
Physical-chemical Characteristics			
Shrinkage (%)	37.77	60.43	52.61
Weight loss (%)	57.10	63.72	57.92
Water activity	0.82	0.63	0.71
Color			
L*	24.79	29.11	28.79
a*	14.08	4.79	7.64
b*	7.56	6.98	10.89
ΔE	14.16	8.92	6.88
Textural Characteristics			
Tensile Force (N)	61.9	184.6	176.7
Puncture Force (N)	43.59	42.84	57.92
Hardness (N)	54.79	85.84	26.39
Cohesiveness	0.71	0.87	0.83
Gumminess (N)	37.86	74.00	13.58
Springiness	0.86	0.86	0.86
Chewiness (N)	33.98	63.74	12.77
Resilience	0.33	0.64	0.52

In the forced-air thin-layer drying method, the drying rate was improved from 0.30 kg of water per kg of dry matter per h to 0.778 kg of water per kg of dry matter per h of smokehouse due to the high forced air movement (1.45 m/s) and low relative humidity (15%) and it took 3 h to dry the samples. The novel hybrid microwave-convection drying uses both microwave energy and convection mode to dry the samples. It improved the drying time from 7 h to 8.25 min with a drying rate of 16.360 kg of water per kg of dry matter per h. Drying constants were also influenced by the method of drying. Product temperatures of the products dried under different methods reached 71°C or higher as per USDA recommendation. The combined microwave-convection drying method gave promising results in terms of energy and time efficiency, which can result in high production volume and low production cost.

Physical-chemical characteristics of beef jerky measured for three different drying methods showed that jerky dried in the forced-air thin-layer dryer possessed a higher volume loss (60.43%) and weight loss (63.72%) than by the other methods. It was observed that hybrid microwave-convection drying has the potential to save 16.42% shrinkage loss and 0.71% weight loss compared to the smoke-house processing method. Water activity of beef jerky processed by different methods was measured as 0.82 for microwave-convection, 0.63 for thin-layer, and 0.71 for smoke house processing methods. Water activity is one of the measures to identify the product stability. All values fell within the safe range (<0.85).

Color parameters of beef jerky dried in different methods indicated that thin layer drying was much closer to the color values achieved for smoke-house processing. Hybrid mw-convection drying produced beef jerky with lighter and reddish color.

Textural characteristics measured have shown significant differences among drying methods. Beef jerky processed in combined microwave-convection drying were softer and had lower tensile and puncture properties compared with other drying methods. These softer products may attract the consumer group who are urging for softer beef jerky. The lowest puncture force value was observed in thin layer (TL) dried samples. However, the difference between TL and microwave drying in puncture properties was not significant. The lowest hardness value was found in smoke-house processed jerky and mw processed were found to be harder than other methods. This can be due to the faster drying ie., higher drying rate. The chewiness value was high for TL dried jerky. It was also noticed that combined microwave-convection dried samples had higher chewability than smoke-house processed jerky. The textural characteristic is one of the most important parameters that defines the commercial value and acceptability. The conclusion can't be driven from one textural property alone, as all the different methods have shown different test results. From the three tests, combined mw-convection drying proved to make softer jerky than the others. Whereas, the samples dried in a thin layer were closer to the samples processed in a smokehouse. The samples processed in smoke house were similar to the commercially available jerky.

To summarize, combined microwave-convection drying has the potential to produce beef jerky with lighter color and softer texture than the commercially available one. As the drying time, weight and volume losses are significantly reduced in combined microwave-convection drying, it promises high production in a short time. High losses in terms of volume and weight were found in thin-layer drying. Also, as the water activity was lower compared to other methods, it ended up as a harder product than the ones processed using other methods. However, samples dried in a thin-layer drying method had similar color and texture like the one processed in a smoke house.

CHAPTER V

SUMMARY AND CONCLUSIONS

5.1. Summary

A growing market for beef jerky urges the need for the improvement of the processing conditions. Traditional methods of processing such as smoke house and home dehydrators take 6-10 h to produce, which leads to high production cost.

There has been no research work done on drying behavior of beef jerky, which is the key to the processing and further improvement of the process. To date, the only method used in practice to prepare jerky is smoke house processing. Alternative processing methods need to be investigated to reduce the processing time. As there are varieties of drying methods available to pursue, one of the current technologies of hybrid microwave (mw) utilization was chosen to check the feasibility of its application in jerky processing. Hybrid microwave technology has shown promising drying time reduction for other food and agricultural material processing. A first attempt to investigate the drying and other quality characteristics of beef jerky using combined microwave-convection drying was made. The effects of salt in beef jerky have also never been studied.

This study was designed to address the issues of alternative drying methods and the existing knowledge gap. Effects of salt and pH, which are the parameters important to product stability, were investigated using a combined microwave-convection drying method. Three pH levels and 3 salt content levels were used to test the influence of pH and salt in jerky processing. Samples with these nine treatments were prepared and dried in combined microwave-convection drying unit. The physical, chemical and textural characteristics of the dried jerky samples were measured and analyzed.

Effects of relative humidity and airflow rate in thin-layer drying on jerky properties were also investigated. This was accomplished by testing two relative humidities and two airflow rates in a forced-air thin-layer drying unit. The physical, chemical and textural characteristics of the dried jerky samples were measured and analyzed.

To compare the advantages of these drying methods, samples with same initial conditions were dried in combined microwave-convection drier, forced air thin layer drier and smoke-house oven. The physical, chemical and textural characteristics of the dried jerky samples were measured and analyzed. The results were compared.

5.2. Conclusions

The conclusions drawn from the results obtained in this study are presented below.

1. pH and salt content had a significant influence on drying characteristics of beef jerky dried in combined microwave-convection drying. Drying rate increased in low pH samples. Increasing the salt content increased the drying rate and reduced the drying time. It was observed that samples with the combination of 3.28% (w/w) salt and pH 5.15 had the highest drying rate (19.5 kg of water per kg of dry matter per h) and, as result, it has the lowest drying time (5.5 min).

   A close examination of the physical-chemical characteristics showed that both pH and salt content significantly influenced the volume and weight loss, and the water activity. Samples with high pH had high losses and low water activities. Samples with pH 5.65 and 1% salt content had the lowest weight loss and shrinkage. The water activities of beef jerky dried using combination of microwave-convection drying were within the range of 0.86 to 0.68. Samples with low pH (5.15) and high salt (3.28% (w/w)) were found to be darker in color than others. Also, it was observed that lowering the pH changed the color significantly by producing darker colored beef jerky. The puncture force of beef jerky dried in combined microwave-convection drier was not significantly influenced by pH, but by salt content. Combination of 1.28% (w/w) salt content and pH 5.65 treatment produced the softest textural characteristics (Puncture force 30.87 N; tensile force 31.10 N; hardness 35.890 N).

Overall, jerky with low pH and high salt content had the best drying characteristics. However, it was observed that jerky at pH 5.65 (control) and 1.28% (w/w) salt content had low losses in terms of weight and dimension. Also, this treatment combination produced softer jerky than the others.

2. The effect of relative humidity and airflow rate was significant for forced-air thin-layer drying characteristics of beef jerky. Samples dried at relative humidity of 15% and airflow rate of 1.45 m/s showed better drying characteristics than other treatments. Physical-chemical properties such as shrinkage, weight loss, water activity and color were found to be influenced by the relative humidity and airflow rate. The combination of 40% relative humidity and 1 m/s airflow rate had lower weight and shrinkage losses compared to others. The textural characteristics of the samples measured showed that drying with 40% relative humidity hot air and 1 m/s airflow rate produced softer products than the rest of the treatments (Puncture force 16.77 N; tensile force 101.7 N; hardness 13.993 N).

3. A comparison of drying methods with respect to drying and physical-chemical characteristics showed that combined microwave-convection was the best alternative drying method among thin-layer drying, smoke house processing and microwave. It reduced the 14.87% (v/v) shrinkage and 0.82% weight loss. Significant percentage (98%) of reduction in time and improved drying rate confirms the possible improvements in processing of jerky using mw hybrid technology. Moreover, the microwave-convection method produced softer jerky compared to the other two methods of drying. Thin-layer drying has the capability to produce samples with similar textural characteristics with smoke-house dried ones, which is the representative of the commercially available jerky.

CHAPTER VI

RECOMMENDATIONS FOR FUTURE WORK

- In this study, the process behavior of beef jerky and its influence of salt (NaCl) as a main ingredients, was studied. To completely understand the processing behavior, effects of other ingredients such as curing agent, sugar and spices in drying and textural characteristics of beef jerky needs to be investigated.

- Microwave – convectional drying method was identified as an alternate way of processing beef jerky. The importance of dielectric properties and material interaction need to be further studied and specific measurements should be done for complete understanding of the heating behavior.. The advantages of other novel drying methods such as infra-red, vacuum-assisted microwave drying, etc. in jerky processing needs to be investigated and compared.

- Modeling and simulation of the drying processes including kinetics of product quality changes for process control and optimization should be performed.

- Energy and cost analysis of utilization of microwave energy in jerky processing needs to be done to commercialize the potential alternate drying methods in jerky processing.

- For marketing, the consumer acceptability of the samples made using different drying methods should be known. To achieve this, sensory evaluation by consumer panelists should be carried out, which is not done in this study.

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APPENDIX- A

Table A1. Nutritional value of restructured beef jerky (100 g) (http://www.calorie-counter.net/beef-calories/beef-jerky.html, 2008)

Composition	Unit	Amount
Water Content	g	23.36
Calorie	Kcal	410
Protein	g	33.2
Fat	g	25.6
Ash	g	6.8
Carbohydrate	g	11
Dietary Fiber	g	1.8
Sugar	g	9
Calcium	mg	20
Iron	mg	5.42
Magnesium	mg	51
Phosphorus	mg	407
Potassium	mg	597
Sodium	mg	2213
Zinc	mg	8.11
Copper	mg	0.227
Manganese	mg	0.111
Selenium	µg	10.7
Thiamin	mg	0.154
Riboflavin	mg	0.142
Niacin	mg	1.732
Pantothenic acid	mg	0.163
Vitamin B6	mg	0.179
Folate	µg	134
Vitamin B12	µg	0.99
alpha tocopherol	µg	0.49

APPENDIX-B1

The drying curves of the beef jerky dried in combined microwave-convection drying is shown in figures B1-B9.

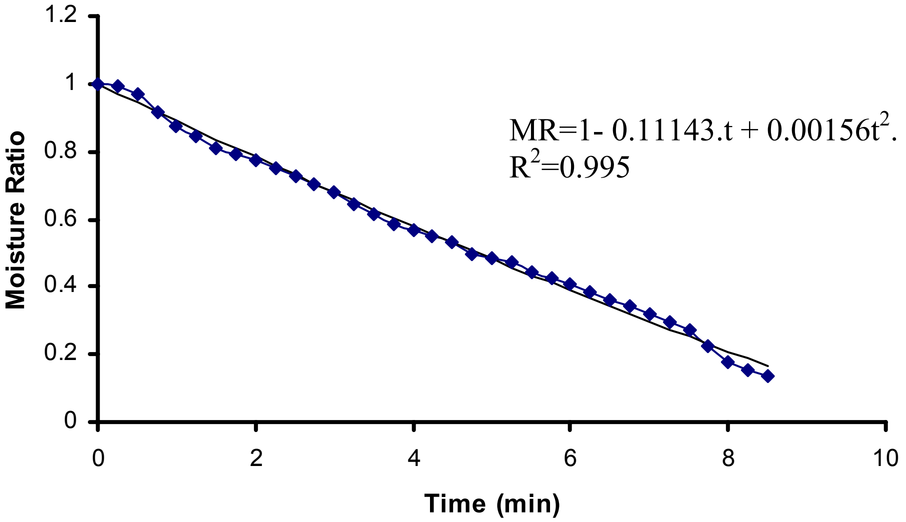

Figure B1. Drying curve of the jerky sample having pH 5.65 and 1.28% (w/w) salt content dried in combined microwave-convection drying.

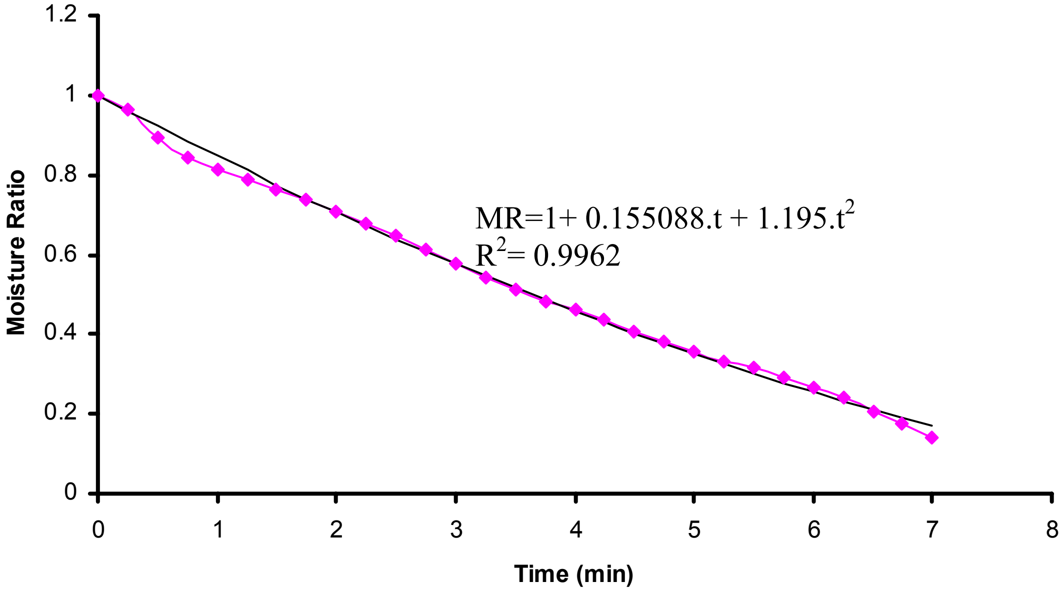

Figure B2. Drying curve of the jerky sample having pH 5.30 and 1.28% (w/w) salt content dried in combined microwave-convection drying.

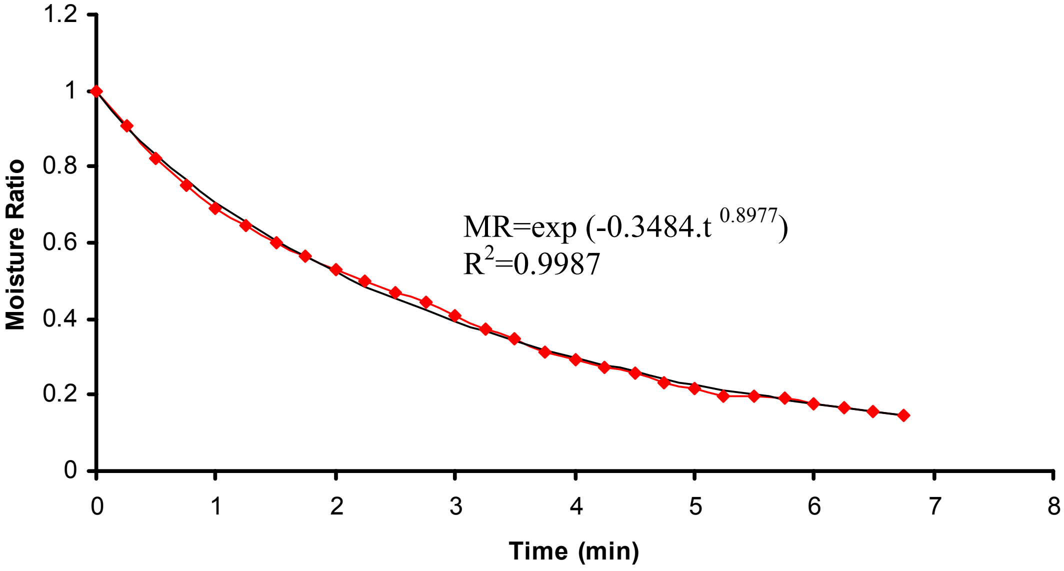

Figure B3. Drying curve of the jerky sample having pH 5.15 and 1.28% (w/w) salt content dried in combined microwave-convection drying.

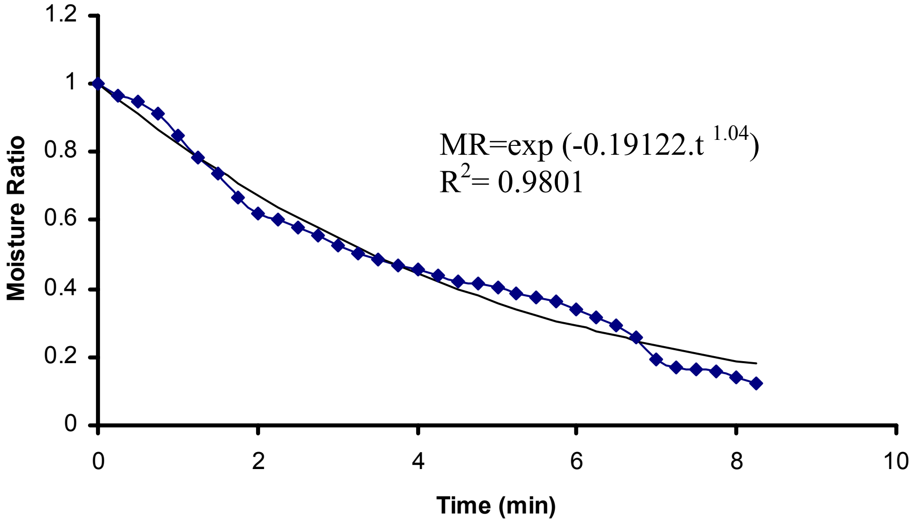

Figure B4. Drying curve of the jerky sample having pH 5.65 and 2.28% (w/w) salt content dried in combined microwave-convection drying.

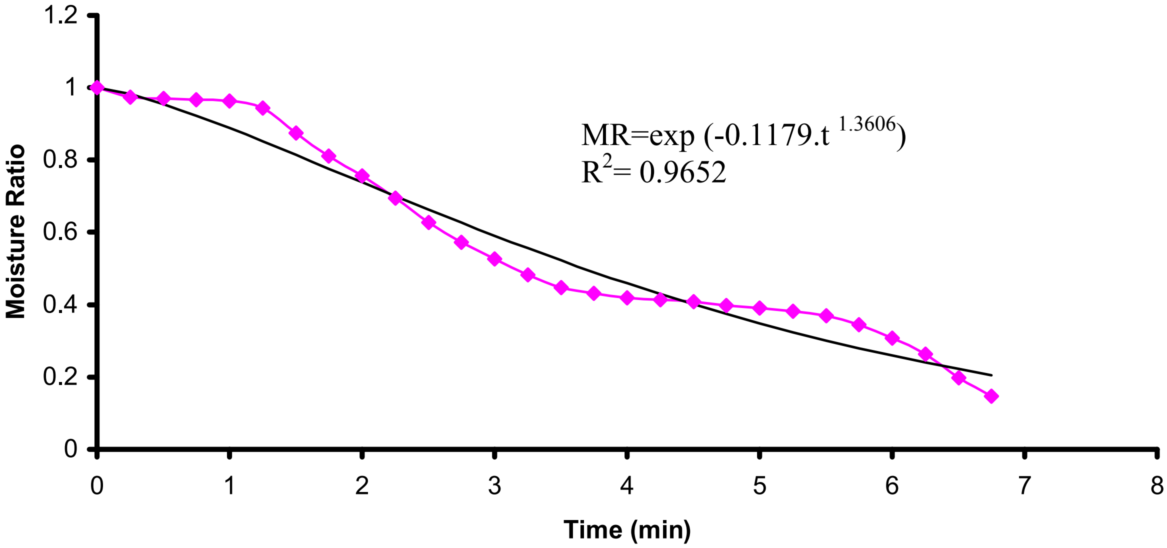

Figure B5. Drying curve of the jerky sample having pH 5.30 and 2.28% (w/w) salt content dried in combined microwave-convection drying.

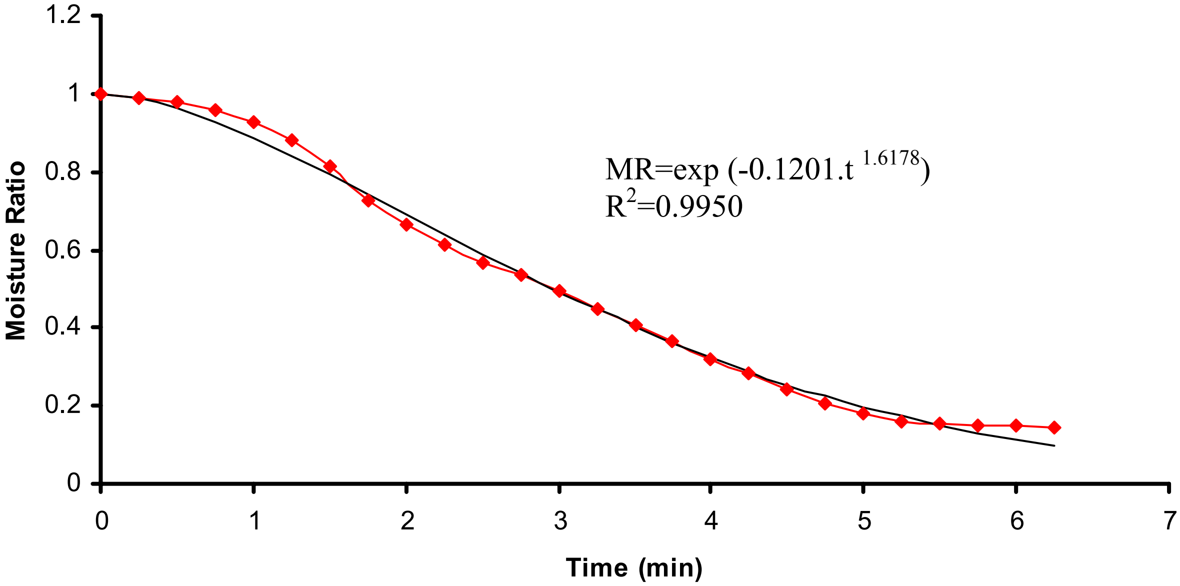

Figure B6. Drying curve of the jerky sample having pH 5.15 and 2.28% (w/w) salt content dried in combined microwave-convection drying.

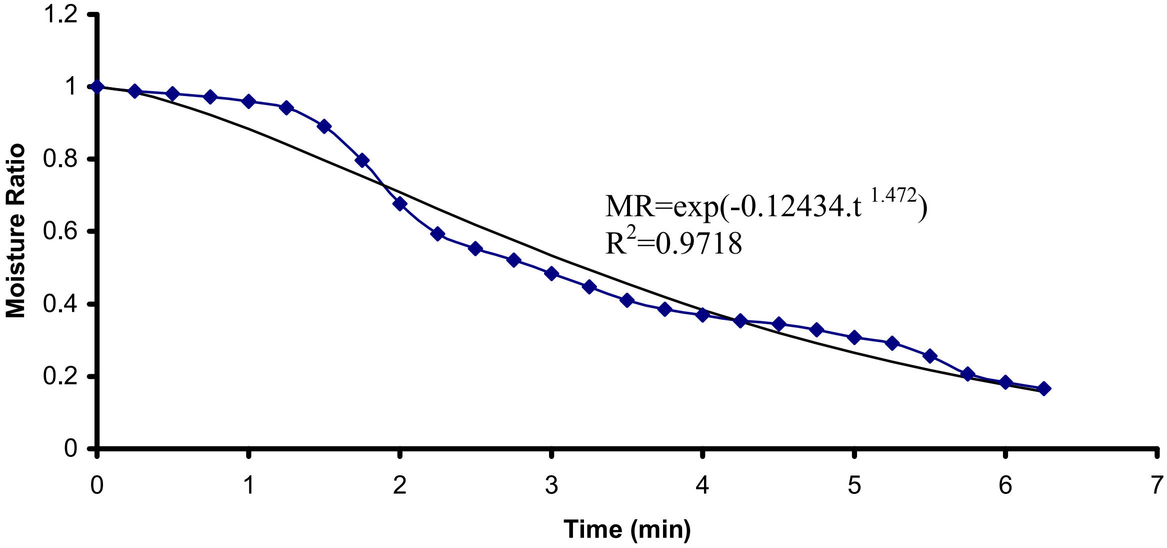

Figure B7. Drying curve of the jerky sample having pH 5.65 and 3.28% (w/w) salt content dried in combined microwave-convection drying.

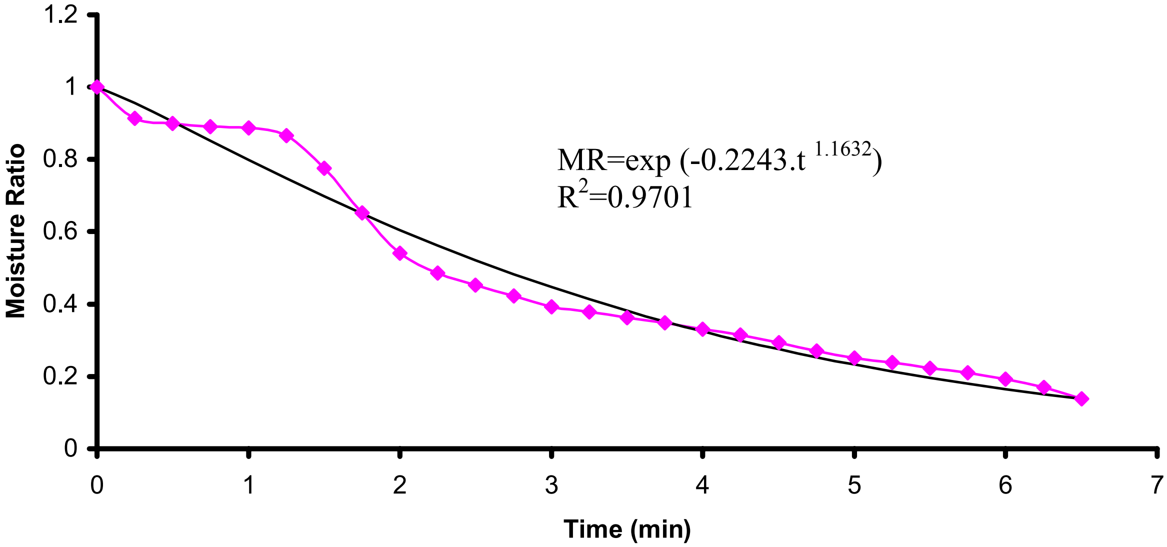

Figure B8. Drying curve of the jerky sample having pH 5.30 and 3.28% (w/w) salt content dried in combined microwave-convection drying.

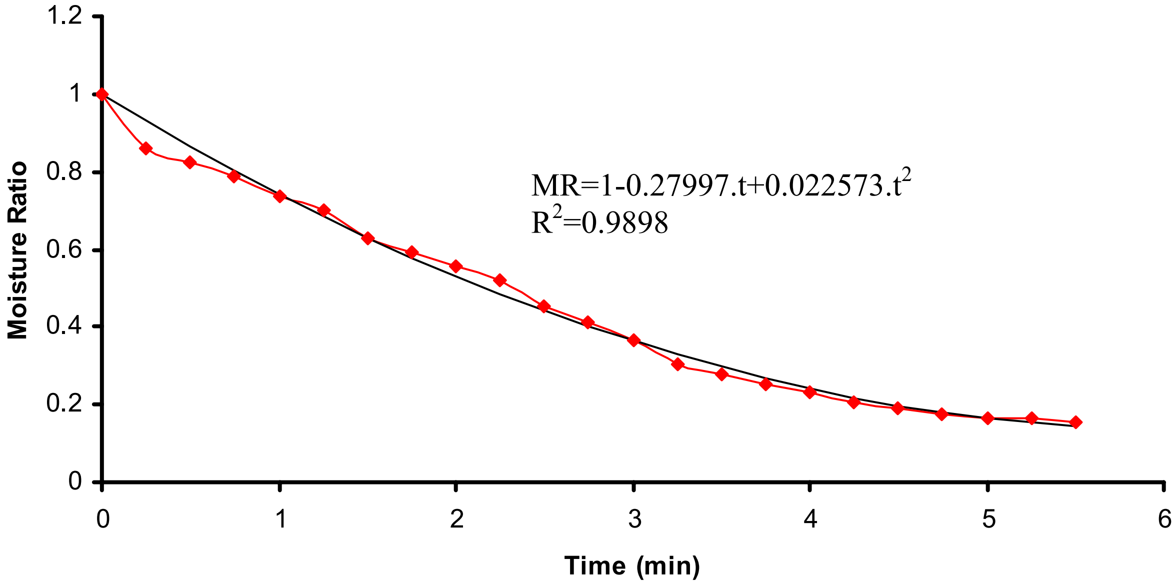

Figure B9. Drying curve of the jerky sample having pH 5.15 and 3.28% salt content dried in combined microwave-convection drying.

APPENDIX B2

The drying rate curves of beef jerky dried in forced-air thin-layer drier in shown in figure B10-B13.

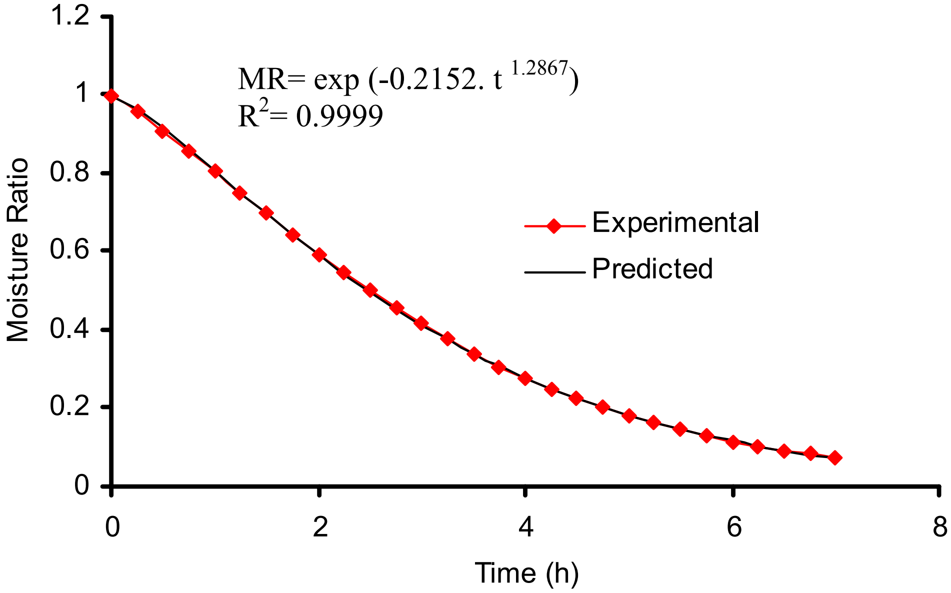

Figure B10. Drying curve of beef jerky dried in thin layer drying unit with 40% relative humidity and 1 m/s air flow rate.

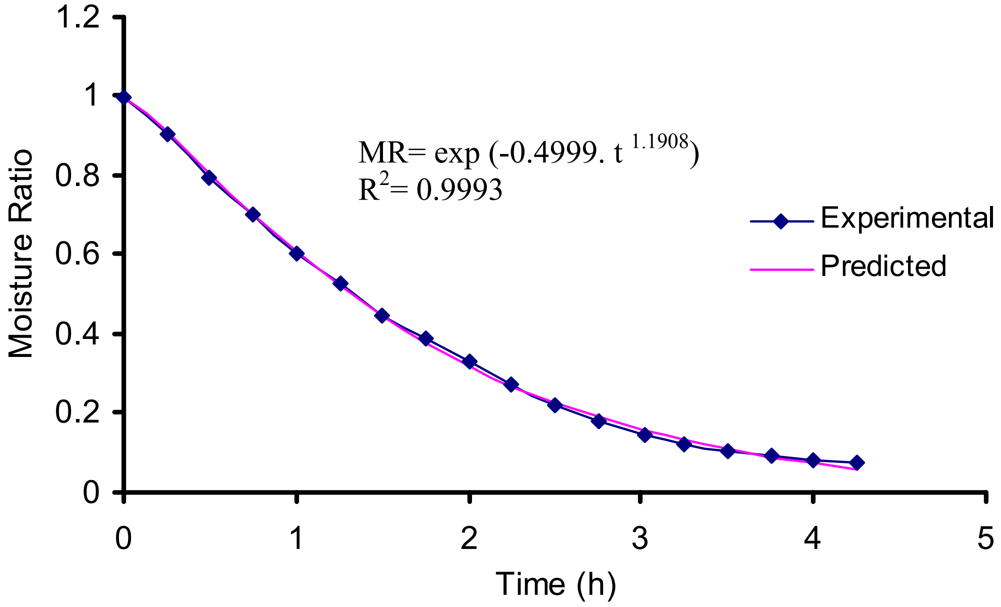

Figure B11. Drying curve of beef jerky dried in 15% relative humidity and 1 m/s air flow rate.

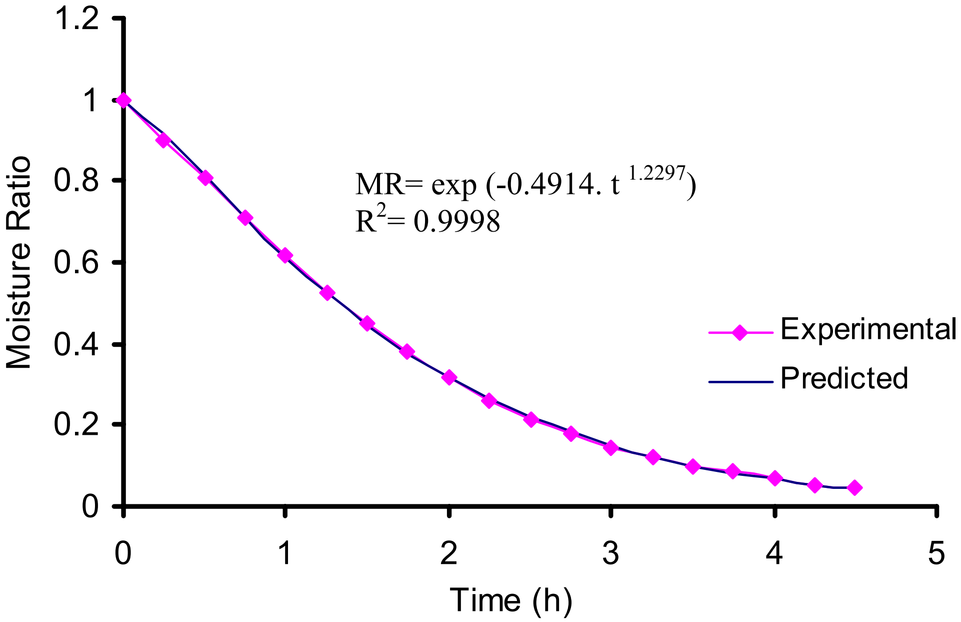

Figure B12. Drying curve of beef jerky dried in 40% relative humidity and 1.45 m/s air flow rate.

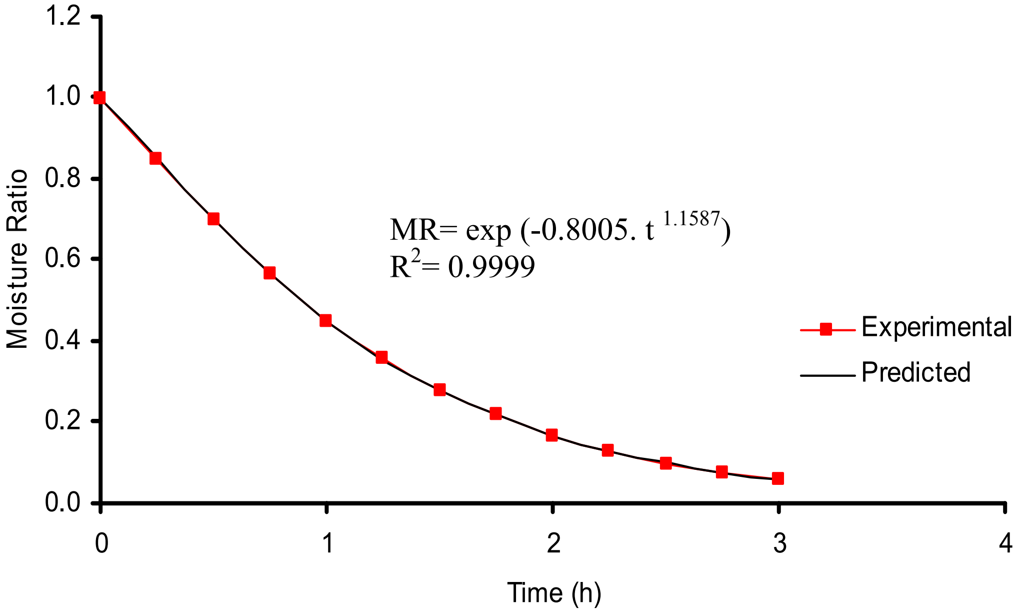

Figure B13. Drying curve of beef jerky dried in 15% relative humidity and 1.45 m/s air flow rate.

APPENDIX C

Drying constants of beef jerky dried using combined microwave-convection drying derived from their drying data are shown in Table C1 with their statistical significance values (t and p values).

Table C1. Statistical results of curve fitted data of beef jerky dried in combined microwave-convection drying

pH	Salt Content % (w/w)	Drying Constants	Std. Error	t-value	95% Confidence		P > t
5.65	1.28	a1 = -0.1114	0.0024	-45.863	-0.116	-0.106	0
		a2 = 0.0016	0.0003	4.291	0.001	0.002	0
	2.28	K= 0.1912	0.0124	15.319	0.165	0.216	0
		n = 1.0416	0.0413	25.179	0.957	1.125	0
	3.38	K = 0.1243	0.0153	8.128	0.093	0.155	0
		n = 1.4719	0.0888	16.576	1.288	1.655	0
5.30	1.28	a1 = 0.1551	0.0084	18.450	0.138	0.172	0
		a2 = 1.1951	0.0365	32.662	1.119	1.270	0
	2.28	K= 0.1180	0.0148	7.9465	0.0872	0.148	0
		n = 1.3606	0.0851	15.995	1.186	1.535	0
	3.38	K= 0.2243	0.0200	11.236	0.183	0.265	0
		n = 1.1632	0.0665	17.481	1.026	1.300	0
5.15	1.28	K= 0.3484	0.0046	76.238	0.339	0.357	0
		n = 0.8977	0.0100	90.149	0.877	0.918	0
	2.28	K= 0.1201	0.0067	17.800	0.106	0.134	0
		n = 1.6178	0.0420	38.509	1.531	1.704	0
	3.38	a1 = -0.2797	0.0061	-45.767	-0.292	-0.267	0
		a2 = 0.0226	0.0014	16.068	0.0196	0.025	0