DETERMINATION OF THE EFFECTS OF MODIFIED ATMOSPHERE PACKAGING AND IRRADIATION ON SENSORY CHARACTERISTICS, MICROBIOLOGY, TEXTURE AND COLOR OF FRESH-CUT CANTALOUPE USING MODELING FOR PACKAGE DESIGN

By

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2004
To my parents & grandparents.
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TABLE OF CONTENTS

page

ACKNOWLEDGMENTS ........................................................................................................ iv

LIST OF TABLES .................................................................................................................. viii

LIST OF FIGURES ........................................................................................................... x

ABSTRACT ....................................................................................................................... xiii

CHAPTER

1 INTRODUCTION ........................................................................................................ 1

2 LITERATURE REVIEW ............................................................................................. 6

   Cantaloupe .................................................................................................................... 6
   Respiration ................................................................................................................... 7
   Fresh-cut ...................................................................................................................... 10
   Flavor .......................................................................................................................... 13
   Modified Atmosphere Packaging .............................................................................. 13
   Modeling .................................................................................................................... 19
   Michaelis-Menten ..................................................................................................... 22
   Irradiation .................................................................................................................. 25

3 EFFECTS OF IRRADIATION ON FRESH-CUT CANTALOUPE STORED IN AN OPEN SYSTEM ..................................................................................................................... 30

   Introduction ............................................................................................................... 30
   Materials and Methods ............................................................................................ 32
      Fruit Sample ............................................................................................................. 32
      Processing ............................................................................................................... 32
      Dosimetry ............................................................................................................... 34
      Gas Analysis ......................................................................................................... 35
      Microbial Analysis ............................................................................................... 35
      Color Analysis ..................................................................................................... 35
      Texture .................................................................................................................. 36
      Statistical Analysis ............................................................................................. 36
   Results and Discussion ............................................................................................ 37
      Respiration .......................................................................................................... 37
Trial 1 ...........................................................................................................37
Trials 2 and 3 ................................................................................................38
Microbiology ...................................................................................................39
Texture ............................................................................................................44
Color .................................................................................................................45
Conclusions ......................................................................................................48

4 RESPIRATION OF IRRADIATED FRESH-CUT CANTALOUPE AND MODELLING OF RESPIRATION FOR MODIFIED ATMOSPHERE PACKAGING .............................................................................................................49

Introduction.................................................................................................................49
Materials and Methods ...............................................................................................50
Fruit Sample ........................................................................................................50
Processing ..........................................................................................................50
Dosimetery ..........................................................................................................52
Gas Analysis ........................................................................................................52
Modeling ..............................................................................................................52
Film Permeability ................................................................................................54
Modified Atmosphere Package Design ...................................................................56
Results and Discussion ...............................................................................................60
Modeling ..............................................................................................................60
Film Permeability ................................................................................................69
Conclusion ..................................................................................................................71

5 DESIGN OF MODIFIED ATMOSPHERE PACKAGE FOR IRRADIATED FRESH-CUT CANTALOUPE AND EVALUATION WITH DESCRIPTIVE ANALYSIS SENSORY PANEL ...............................................................................72

Introduction ..................................................................................................................72
Materials and Methods ...............................................................................................73
Fruit Sample ........................................................................................................73
Processing ..........................................................................................................73
Dosimetery ..........................................................................................................75
Gas Analysis ........................................................................................................76
Microbial Analysis ..............................................................................................76
Sensory ................................................................................................................76
Color Analysis .....................................................................................................78
Texture .................................................................................................................78
Statistical Analysis ..............................................................................................78
Results and Discussion ...............................................................................................79
MAP Design ........................................................................................................79
Microbiology .......................................................................................................87
Texture ................................................................................................................87
Color .....................................................................................................................90
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Respiration rate ranges of cantaloupe at various temperatures.</td>
</tr>
<tr>
<td>3.1</td>
<td>Texture (max force kg) of irradiated and non-irradiated fresh-cut cantaloupe stored at 3 °C (Trial 3)</td>
</tr>
<tr>
<td>3.2</td>
<td>Texture (max force kg) of irradiated and non-irradiated fresh-cut cantaloupe stored at 3 °C (Trial 3)</td>
</tr>
<tr>
<td>3.3</td>
<td>Color of irradiated and non-irradiated fresh-cut cantaloupe stored at 3 °C (Trial 2)</td>
</tr>
<tr>
<td>3.4</td>
<td>Hue and chroma of irradiated and non-irradiated fresh-cut cantaloupe stored at 3 °C (Trial 2)</td>
</tr>
<tr>
<td>3.5</td>
<td>Color of irradiated and non-irradiated fresh-cut cantaloupe stored at 3 °C (Trial 3).</td>
</tr>
<tr>
<td>3.6</td>
<td>Hue and chroma of irradiated and non-irradiated fresh-cut cantaloupe stored at 3 °C (Trial 3)</td>
</tr>
<tr>
<td>4.1</td>
<td>Coefficients of Eqn. (4.1) and (4.2) describing the changes in oxygen and carbon dioxide concentrations, respectively, over time for irradiated and non-irradiated fresh-cut cantaloupe stored in a closed system at 3 °C</td>
</tr>
<tr>
<td>4.2</td>
<td>Coefficients of Michalis-Menten model Eqn (4.5) and (4.6) for changes in oxygen and carbon dioxide concentrations, respectively, over time for irradiated and non-irradiated fresh-cut cantaloupe stored in a closed system at 3 °C</td>
</tr>
<tr>
<td>4.3</td>
<td>Coefficients of the polynomial model Eqns. (4.10) and (4.11) for changes in oxygen and carbon dioxide concentrations, respectively, over time for irradiated and non-irradiated fresh-cut cantaloupe stored in a closed system at 3 °C</td>
</tr>
<tr>
<td>4.4</td>
<td>Average oxygen (OTR) and carbon dioxide (CO2TR) transmission rates at various temperatures for films tested.</td>
</tr>
<tr>
<td>4.5</td>
<td>Arrhenius relationship values Ea and ko for two films tested</td>
</tr>
</tbody>
</table>
5.1 Headspace composition of modified atmosphere packages of irradiated and non-irradiated fresh-cut cantaloupe stored at 3 °C .................................................................85

5.2 Total plate count (TPC) and yeast and mold count (Y+M) of irradiated and non-irradiated fresh-cut cantaloupe stored at 3 °C in modified atmosphere packages (Trial 1) ...............................................................................................................................88

5.3 Total plate count (TPC) and yeast and mold count (Y+M) of irradiated and non-irradiated fresh-cut cantaloupe stored at 3 °C in modified atmosphere packages (Trial 2) ...............................................................................................................................89

5.4 Texture (kg) of irradiated and non-irradiated fresh-cut cantaloupe during storage at 3 °C in modified atmosphere packages ...........................................................................90

5.5 Color (L*, a*, b*) of irradiated and non-irradiated fresh-cut cantaloupe during storage at 3 °C in modified atmosphere packages, by treatment (Trial 1). .................91

5.6 Color (L*, a*, b*) of irradiated and non-irradiated fresh-cut cantaloupe during storage at 3 °C in modified atmosphere packages, by storage ........................................................................92

5.7 Color (L*, a*, b*) of irradiated and non-irradiated fresh-cut cantaloupe during storage at 3 °C in modified atmosphere packages, by treatment (Trial 2). .................92

5.8 Sensory results (Trial 1), by treatment and over storage of irradiated and non-irradiated fresh-cut cantaloupe (0 to 15 scale), stored at 3 °C .........................................................94

5.9 Sensory results (Trial 2), by treatment and over storage of irradiated and non-irradiated fresh-cut cantaloupe (0 to 15 scale), stored at 3 °C .........................................................95
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Recommended oxygen and carbon dioxide ranges for the storage of some harvested vegetable commodities (Saltveit, 2003)</td>
<td>18</td>
</tr>
<tr>
<td>2.2</td>
<td>Recommended oxygen and carbon dioxide ranges for the storage of few harvested vegetable commodities showing differences within individual commodities (Saltveit, 2003)</td>
<td>19</td>
</tr>
<tr>
<td>2.3</td>
<td>The radura symbol, which is required by U.S. law to be in plain sight on all packages of irradiated foods</td>
<td>26</td>
</tr>
<tr>
<td>3.1</td>
<td>Schematic of cantaloupe being irradiated in Ziploc bags on trays of ice</td>
<td>33</td>
</tr>
<tr>
<td>3.2</td>
<td>Respiration rate (CO₂ production) of irradiated and non-irradiated fresh-cut cantaloupe stored at 3 °C (Trial 1)</td>
<td>38</td>
</tr>
<tr>
<td>3.3</td>
<td>Respiration rate (CO₂ production) of irradiated and non-irradiated fresh-cut cantaloupe stored at 3 °C (Trial 2)</td>
<td>39</td>
</tr>
<tr>
<td>3.4</td>
<td>Respiration rate (CO₂ production) of irradiated and non-irradiated fresh-cut cantaloupe stored at 3 °C (Trial 3)</td>
<td>40</td>
</tr>
<tr>
<td>3.5</td>
<td>Total plate count (TPC) of irradiated and non-irradiated fresh-cut cantaloupe stored at 3 °C (Trial 2)</td>
<td>40</td>
</tr>
<tr>
<td>3.6</td>
<td>Yeast and Molds counts of irradiated and non-irradiated fresh-cut cantaloupe stored at 3 °C (Trial 2)</td>
<td>41</td>
</tr>
<tr>
<td>3.7</td>
<td>Total plate count (TPC) of irradiated and non-irradiated fresh-cut cantaloupe stored at 3 °C (Trial 3)</td>
<td>42</td>
</tr>
<tr>
<td>3.8</td>
<td>Yeast and Molds counts of irradiated and non-irradiated fresh-cut cantaloupe stored at 3 °C (Trial 3)</td>
<td>42</td>
</tr>
<tr>
<td>4.1</td>
<td>The input screen for all data necessary for the prediction program with variables described and units defined</td>
<td>59</td>
</tr>
<tr>
<td>4.2</td>
<td>Percent oxygen and carbon dioxide in headspace during closed system storage of irradiated and non-irradiated fresh-cut cantaloupe at 3 °C</td>
<td>62</td>
</tr>
</tbody>
</table>
4.3 Michaelis-Menten equation fit to observed respiration data vs. percent oxygen for non-irradiated fresh-cut cantaloupe stored in a closed system at 3 °C........................................64

4.4 Michaelis-Menten equation fit to observed respiration data vs. percent carbon dioxide for non-irradiated fresh-cut cantaloupe stored in a closed system at 3 °C...........................................................................................................................65

4.5 Second order polynomial equation fit for observed respiration data vs. percent oxygen within the critical range for non-irradiated fresh-cut cantaloupe stored in a closed system at 3 °C.............................................................................................................................67

4.6 Polynomial equation fit to observed respiration data vs. percent carbon dioxide for within the critical range for non-irradiated fresh-cut cantaloupe stored in a closed system at 3 °C. ..........................................................................................................................68

4.7 Arrhenius relationship between the natural log of the oxygen transmission rate (O2TR) in ml/m²/day and temperature for two films tested. .................................................70

4.8 Arrhenius relationship between the natural log of the carbon dioxide transmission rate (CO2TR) in ml/m²/day and temperature for two films tested. .......................71

5.1 Predicted oxygen and carbon dioxide partial pressures for 0.4 kGy samples in designed modified atmosphere package with initial gas flush of 4% O₂ plus 10% CO₂ for Trial 1 stored at 3 °C..................................................................................................................80

5.2 Predicted oxygen and carbon dioxide partial pressures for 0.4 kGy samples in designed modified atmosphere package with initial gas flush of 4% O₂ plus 10% CO₂ for Trial 2 stored at 3 °C. .........................................................................................................................81

5.3 Actual oxygen partial pressures for all samples in designed modified atmosphere packages for Trial 1 stored at 3 °C..........................................................................................................................82

5.4 Actual carbon dioxide partial pressures for all samples in designed modified atmosphere packages for Trial 1 stored at 3 °C. .................................................................82

5.5 Actual oxygen partial pressures for all samples in designed modified atmosphere packages for Trial 2 stored at 3 °C.................................................................83

5.6 Actual carbon dioxide partial pressures for all samples in designed modified atmosphere packages for Trial 2 stored at 3 °C.................................................................83

5.7 Trial 1 Predicted and observed oxygen and carbon dioxide levels inside designed modified atmosphere package containing irradiated fresh-cut cantaloupe stored at 3 °C..................................................................................................................86
5.8 Trial 2 predicted and observed oxygen and carbon dioxide levels inside
designed modified atmosphere package containing irradiated fresh-cut
cantaloupe stored at 3 °C......................................................................................................................87

5.9 Off flavor rating of treatments at each storage (3 °C).........................................................97

5.10 Acceptability rating of treatments at each storage date (3 °C)...........................................97

5.11 Sweetness rating of treatments at each storage (3 °C). .......................................................99

5.12 Cantaloupe flavor intensity (CFI) rating of treatments at each storage date
(3 °C)...................................................................................................................................................100

5.13 Off flavor rating of treatments at each storage date (3 °C). ...............................................101

5.14 Acceptability rating of treatments at each storage date (3 °C).................................101
Abstract of Dissertation Presented to the Graduate School of the University of Florida in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy

DETERMINATION OF THE EFFECTS OF MODIFIED ATMOSPHERE PACKAGING AND IRRADIATION ON SENSORY CHARACTERISTICS, MICROBIOLOGY, TEXTURE AND COLOR OF FRESH-CUT CANTALOUPE USING MODELING FOR PACKAGE DESIGN

By

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Chair: Charles Sims
Cochair: Bruce Welt
Major Department: Food Science and Human Nutrition

Objectives of this project were to determine effects of irradiation and modified atmosphere packaging on fresh-cut cantaloupe (Cucumis melo Linnaeus reticulatus). Fresh-cut cantaloupe was exposed to doses (0.1-1.5 kGy) of electron beam irradiation and stored in open systems at 3°C. Microbial counts were consistently reduced in sympathy with irradiation dose. Respiration rates were slightly higher in the irradiated samples compared to non-irradiated control within the first 24 hours and converged thereafter. Respiration rates of all samples remained similar until 7-10 days of storage when controls increased significantly. Higher irradiation levels delayed the onset of increased respiration. Samples irradiated at 0.3, 0.6, and 0.9 kGy were significantly less firm than non-irradiated samples only within 2 hrs of treatment during 13 days of storage.
Fresh-cut cantaloupe were irradiated at 0, 0.2, 0.4, and 0.6 kGy and stored in hermetically sealed containers at 3°C. Oxygen and carbon dioxide levels were measured over time. Attempts to fit respiration data to many common functions were unsuccessful, including the Michaelis-Menten enzyme equation, which is often used for this purpose. Therefore, polynomial equations were used. Arrhenius equations were used to describe temperature sensitivity of transmission rates for oxygen and carbon dioxide for two films commonly used in the fresh-cut industry.

A computer program was written with Visual Basic for Applications using Microsoft Excel, which was used as an aid to design a modified atmosphere package based on predicted respiration and gas permeation rates. This package was used in a subsequent study to determine combined effects of irradiation and modified atmosphere on quality and sensory changes during storage.

Irradiated samples (0.5 and 1.0 kGy) had a lower and more stable rate of respiration than non-irradiated samples over the duration of the study. Color and texture remained stable for the duration of each study as measured by instrument and sensory panel. Sensory evaluation rated the 1.0 kGy sample highest in sweetness and cantaloupe flavor intensity and lowest in off flavor after 17(±3) days storage. The program and model predicted respiration rates well. Low dose electron beam irradiation of fresh-cut cantaloupe with modified atmosphere packaging offers promise as a method of extending shelf-life.
CHAPTER 1
INTRODUCTION

Melon is the fourth largest produced fruit, by weight production, in the world (18,000,000 tons) behind orange, banana and grape. In 1999, the United States of America (USA) was third in melon production with 1,320,850 tons, behind China at 5,806,384 tons and Turkey at 1,800,000 tons (Aguayo and others, 2004). The word “cantaloupe” is often used, especially in the USA, to describe the netted melon or muskmelon (Cucumis melo, var. reticulatus). A true cantaloupe is a non-netted fruit popular in Cantaluppi, Italy, and rarely grown in the USA (Shellie and Lester, 1999). In 1997, Florida cantaloupe acreage made up about one percent of the USA cantaloupe acreage.

Fresh-cut products, also known as lightly processed or minimally processed (Watada and others, 1996), offer convenience and reduced waste. Demand for fresh cut fruits and vegetables has been increasing greatly in the USA for the past 10 years and is still considered in its infancy (Suslow and Cantwell, 2001). Fresh cut products have been available for many years, but in the past decade the types and quantity have expanded greatly. The sales of fresh-cut fruit have grown linearly approximately $1 billion per year (Anonymous, 1999a), due largely to increased regional production and distribution. Around 10% of all fresh fruits and vegetables sold in the USA in 1998 were fresh-cut sales at $8.8 billion, and sales in 2004 should reach $15 billion (Anonymous, 1999b). The food service industry has been the primary purchaser of fresh-cut products in the past, but warehouse stores, restaurants, and supermarkets have become major purchasers with
increasing sales. The International Fresh-cut Produce Association (IFPA) purposefully chose the term fresh-cut to include the word fresh. In order for something to be labeled fresh-cut, it must meet the FDA’s current definition of the term fresh, which requires that produce be alive, actively respiring and carrying out the metabolic and biochemical activities of life. The IFPA supports the use of the term “fresh-cut” for labeling products treated by processes that do not cause respiration to cease (Gorny, 2000).

The goal of fresh-cut products is to deliver convenience and high quality. Therefore, fresh-cut products must not only be aesthetically pleasing, but also comply with food safety requirements. Consumers expect fresh-cut products to be without defects, of optimum maturity, fresh appearance, and have high sensory and nutrient quality (Watada and Qi, 1999). Fresh-cuts are usually more perishable than uncut whole fruit, due to extreme physical stresses from processes such as peeling, cutting, slicing, shredding, trimming, coring, and removal of protective epidermal cells (Watada and others, 1996). High quality of raw product is necessary to achieve high quality fresh-cut product. Final product can only be as good as the incoming raw product.

Quality of fresh-cut produce is directly related to wounding associated with processing. Physical wounding and damage also induce additional deleterious physiological changes within produce (Brecht, 1995; Saltveit, 1997). Symptoms can be visual, such as deterioration from flaccidity with water loss, changes in color, especially browning at the surfaces, and microbial contamination (Brecht, 1995; King and Bolin, 1989; Varaquaux and Wiley, 1994). Wounding also leads to alterations in flavor and production of aroma volatile (Moretti and others, 2002).
One of the first responses to wounding is a transient increase in ethylene production and an enhanced rate of respiration. Increased respiration can lead to excessive losses of water and nutrients (Brecht, 1995). Generally, tissues with high respiration rates and/or low energy reserves have shorter postharvest lives (Eskin, 1990). Ethylene can also stimulate other physiological processes, causing accelerated membrane deterioration, loss of vitamin C and chlorophyll, abscission, toughening, and undesirable flavor changes in many horticultural products (Kader, 1985). Wounding also allows for easier attack and survival of plant pathogenic microorganisms and food poisoning microorganisms.

Radiation research directed towards the preservation of foods began in 1945 (Karel, 1975). “Irradiation” or “food irradiation” generally refers to the use of gamma rays from radionuclides such as $^{60}\text{Co}$ or $^{137}\text{Cs}$, or high-energy electrons and X-rays produced by machine sources to treat foods. Electron beams (e-beams) can be emitted from the cathode of an evacuated tube subjected to an electrical potential or produced in linear accelerators (Karel, 1975). The energy of the electron beams is limited to 10 MeV for use in food treatment (Rosenthal, 1992). Using good manufacturing practices, irradiated foods have been established to be safe, wholesome and without residues (Farkas, 1998). Two major benefits of irradiation are that a product can be treated in its final package as a terminal treatment (Farkas, 1998), and the temperature of the product is not significantly affected.

In a paper by Minea and others (1996), strawberries, cherries, apricots, and apples were irradiated with an electron accelerator at doses of 0.1 - 3 kGy at dose rates from 100 to 1500 Gy/min. Results showed very effective microbial destruction and a great influence on the decrease of enzymatic activities. Shelf life extension of at least 4-7
days was achieved with sensory properties not significantly affected. There were no significant changes in the physical and chemical properties of irradiated fruit.

Respiration involves the consumption of oxygen and production of carbon dioxide, water and chemical energy in the form of ATP. Aerobic respiration can be slowed by limiting available oxygen. However, oxygen must be maintained above a minimum threshold to prevent anaerobic respiration (Knee, 1980). Additionally, increased carbon dioxide concentration has been shown to slow down ripening and respiration rates (Mathooko, 1996). Therefore, an optimal atmosphere may be created via modified atmosphere packaging (MAP), where respiration and ethylene production may be reduced as well as many other degrading processes. A MAP can be developed by matching the proper package and film with an appropriate amount of fruit with a given respiration rate.

Modified atmosphere packages can be designed using predictive equations based on known respiration data. Respiration rate for most produce depends on the oxygen and carbon dioxide levels that surround the produce. An ideal package will maintain the desired levels of decreased oxygen and increased carbon dioxide based on the transmission rates of the package and the respiration rate of the produce at the desired storage temperature. Packages can be flushed with the desired steady-state gas composition in order to more quickly achieve equilibrium conditions. The sooner the produce is brought to optimal atmospheric conditions the more effective the package.

A combination of MAP and irradiation may have a synergistic effect on the shelf life of produce. This was demonstrated by Prakash and others (2000) using cut romaine lettuce. Irradiation increased the shelf life of the MAP fresh-cut lettuce as compared to
the non-irradiated MAP fresh-cut lettuce by reducing the initial microbial load 1.5 log CFU/g and maintaining a 4 log CFU/g difference on the 18th day of storage.

The purpose of this research had three main objectives. The first was to determine the effects of irradiation on fresh-cut cantaloupe with regard to respiration rate, color, microbiology and texture during storage. The second was to use respiration data of irradiated and non-irradiated fresh-cut cantaloupe to model oxygen and carbon dioxide concentrations over time in a MAP. The final objective was to use the model to design a MAP and test its effectiveness in maintaining fresh-cut cantaloupe quality using a trained descriptive analysis panel and determine the designed MAP effects on product color, microbiology and texture.
CHAPTER 2
LITERATURE REVIEW

Cantaloupe

Cantaloupe (Cucumis melo) is a member of the Cucurbitaceae family. Cucurbits, of which squash, cucumbers and watermelon are all a part, originated in different locations. The cantaloupe is believed to have originated in Africa.

Within the Cantaloupensis group, muskmelon fruit are classified into two major categories in the USA, the eastern and western type cantaloupe. The eastern cantaloupe is distinct by its sutured and netted surface and it has a spherical or elongated oval shape. Easterns also have relatively large moist seed cavities and soft to medium flesh with strong aroma. Easterns characteristically store poorly with a relatively short storage life. They have been adapted to grow in many climates and are not intended for long transport. The western type cantaloupe is commonly grown in the arid southwestern USA and other countries with similar climate and tends to have a longer shelf-life than easterns (Lamikanra and others, 2003; Rubatzky and Yamaguchi, 1997). Westerns are usually without sutures, extensively netted, with a rugged thick flesh suitable for long distance shipping. Their seed cavity is small and dry. "Super Market," "Summet," "Magnum 45," "Primo," "Mission," "Ambrosia," "Athena," "Cordele," and "Eclipse" are the Eastern Choice type cantaloupes that will grow productively in Florida (Mossler and Nesheim, 2001; Hochmuth and others, 2000). The average harvested yields per acre of cantaloupe crops in Florida have been 150 cwt over the last few years (Hochmuth and others, 2000). Acreage intended for harvest in the USA for 2004 was forecast at 33,300 acres, up 13
percent from 2003 (USDA Economics, Statistics and Market Information System, 2004). Cantaloupe is used more in the fresh-cut industry than any other fruit (Lamikanra and Richard, 2002).

Cantaloupe is prone to chilling injury when stored at temperatures less than 2 °C for several days. Chilling injury sensitivity decreases as melon maturity and ripeness increase. Another source of postharvest loss can be disease, which can depend on season, region and handling practices. Commonly, decay or surface lesions result from fungal pathogens *Alternaria*, *Penicillium*, *Cladosporium*, *Geotrichum*, *Rhizopus*, and to a lesser extent *Mucor*. Cantaloupes are predominantly graded on external appearances and measured soluble solids. U.S. grades are Fancy, No. 1, Commercial and No. 2. Federal Grade Standards specify a minimum of 11% soluble solids for U.S. Fancy ("Very good internal quality") and 9% soluble solids for U.S. 1 ("Good internal quality") (Suslow and others, 2001).

As cantaloupe matures on the vine, the fruit begins to separate at the abscission layer where the stem (peduncle) attaches at the fruit. The maturity level is determined by the degree of separation and called “slip.” Therefore, if the abscission layer is ½ detached, then the maturity level is called ½ slip, if it is ¾ detached, then it is called ¾ slip, etc. A good indicator of full ripeness and harvest time is partial to complete separation. In the USA, ¾ to full slip is the maturity level for commercial practice of harvesting cantaloupe (Beaulieu and others, 2004).

**Respiration**

The word respiration is derived from the Latin word *respirare* which literally means to breathe (Noggle and Fritz, 1983). It was first discovered that humans consume
oxygen and produce carbon dioxide. At the end of the eighteenth century, Dutch plant
physiologist Ingen-Housz discovered that not only animals but also plants respire. It was
well established by the middle of the nineteenth century that all growing cells of higher
plants respire at all times, in the light as well as the dark, using oxygen, oxidizing
carbonaceous substances, and producing carbon dioxide and water.

Glucose is the respiratory substrate most commonly consumed in cellular
respiration. The overall reaction is usually written as

\[ C_6H_{12}O_6 + 6 \text{ O}_2 \to 6 \text{ CO}_2 + 6 \text{ H}_2\text{O} + \text{Heat} \]  \hspace{1cm} (2.1)

However, this reaction omits the fact that oxygen does not react directly with sugar
in respiration. Water molecules are joined with intermediate products during glucose
degradation, one water molecule for each carbon in the sugar molecule. The hydrogen
atoms in intermediate products are joined with oxygen to form water. A more complete
reaction is written as

\[ C_6H_{12}O_6 + 6 \text{ H}_2\text{O} + 6 \text{ O}_2 \to 6 \text{ CO}_2 + 12 \text{ H}_2\text{O} \]  \hspace{1cm} (2.2)

Respiratory substrates commonly consumed are carbohydrates, lipids and organic
acids. The overall sequence of events is referred to as respiratory metabolism. An
abbreviated outline of respiratory metabolism is the process of glucose, in the cytosol,
becoming pyruvic acid through glycolysis, going to the tricarboxylic acid cycle in the
mitochondria and finally the electron transport system. Oxygen is also needed as a
substrate in the respiratory reaction. The gas must travel from the surrounding
environment through intercellular spaces, cell wall, cytoplasm and other membranes of
plant cells. The rate of diffusion will have an effect on respiration rate.
The rate of respiration for fresh-cut produce is measured by the amount of oxygen consumed or carbon dioxide produced per weight of produce for a period of time at a certain temperature. Table 2.1 lists the respiration rates of cantaloupe at various temperatures (Kader, 1992).

Table 2.1. Respiration rate ranges of cantaloupe at various temperatures.

<table>
<thead>
<tr>
<th>Temperature C</th>
<th>mg CO₂ kg⁻¹ h⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5 to 6</td>
</tr>
<tr>
<td>4 to 5</td>
<td>9 to 10</td>
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<tr>
<td>10</td>
<td>14 to 16</td>
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<td>15 to 16</td>
<td>34 to 39</td>
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<td>20 to 21</td>
<td>45 to 65</td>
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<tr>
<td>25 to 27</td>
<td>62 to 71</td>
</tr>
</tbody>
</table>

Ranges exist in respiration rate due to cultivar, growing season and conditions, harvest maturity and technique, and many other factors.

Many methods are available for measuring respiration rate. The most common are the closed or static system, the flowing or flushed system and the permeable system (Fonseca and others, 2002). In the closed system method, a respiring sample is closed in an airtight container with known volume and initial oxygen and carbon dioxide concentrations. Gas samples are taken over time and respiration rate is based on concentration change (Eqns. 2.3 and 2.4).

\[
R_{O_2} = \frac{(y_{O_2 \text{ inf low}} - y_{O_2 \text{ outflow}}) \times V}{100 \times M \times (t_f - t_i)} \tag{2.3}
\]

\[
R_{CO_2} = \frac{(y_{CO_2 \text{ outflow}} - y_{CO_2 \text{ inf low}}) \times V}{100 \times M \times (t_f - t_i)} \tag{2.4}
\]

The flow through system passes gas of known concentrations over the sample in a barrier container. The respiration rate is determined by the differences in the inflow and outflow gases (Eqns. 2.5 and 2.6).
The permeable system uses a package of known gas transmission rates and size filled with sample. Using the permeability and the steady-state concentrations, respiration rate can be determined (Eqns. 2.7 and 2.8).

\[
R_{O_2} = \frac{(y_{O_2,\text{in}} - y_{O_2,\text{out}}) \times F}{100 \times M} \quad (2.5)
\]

\[
R_{CO_2} = \frac{(y_{CO_2,\text{out}} - y_{O_2,\text{in}}) \times F}{100 \times M} \quad (2.6)
\]

\[
R_{O_2} = \frac{P_{O_2} \times A}{100 \times L \times M} \times (y_{eO_2} - y_{O_2}) \quad (2.7)
\]

\[
R_{CO_2} = \frac{P_{CO_2} \times A}{100 \times L \times M} \times (y_{CO_2} - y_{eCO_2}) \quad (2.8)
\]

\(R_{O_2}\) and \(R_{CO_2}\) are respiration rate, oxygen uptake and carbon dioxide evolution, respectively, \(y\) is volumetric concentration, \(V\) is volume, \(M\) is mass, \(t\) is time, \(f\) is final, \(i\) is initial, \(F\) is flow rate, \(A\) is area of package, \(P\) is permeability, \(L\) is thickness and \(e\) is external.

Each system has its limitations and problems, but an accurate range should be able to be achieved.

**Fresh-cut**

The fresh-cut industry continues to grow with technology increasing shelf life and duration of quality. Shelf life of fresh-cut fruits and vegetables ranges from 7 - 20 days when held at optimal temperatures (Watada and Qi, 1999). Fresh-cut cantaloupe had a reduction of “typical” flavor during the first 4 days when stored at 4 °C in rigid barrier containers (O’Connor-Shaw and others, 1994). At 7 days, bitterness levels were lower and the fruit was firmer. At day 11, fruit was paler than originally and white colonies of
microbes were observed. In a study by Ayhan and others (1998), the shelf life of fresh-cut honeydew and cantaloupe was determined. Four treatments were tested: I Fruit was cut without washing, II Fruit was washed with water before cutting, III Whole fruit was dipped in 200 ppm hypochlorite solution and cut fruit was dipped in 50 ppm hypochlorite solution twice, IV Whole fruit was dipped in 2000 ppm hypochlorite solution and cut fruit was dipped in 50 ppm hypochlorite solution twice. All samples were stored in full barrier laminated nylon film at 2.2 °C. A 2 log (CFU/g) reduction of surface aerobic plate count for cantaloupe was observed in treatment III compared to treatment I and a 3.3 log reduction occurred between treatment IV and treatment I. The total psychrotrophic count of the processed cantaloupe was similar with a 3.3 log reduction for both treatment III and IV compared to treatment I at day 0 with a continued 3 log reduction through day 20. Sensory characteristics (odor, taste, overall flavor, texture, appearance and overall acceptance) were evaluated during the 20 day storage of cantaloupe. Treatments III and IV were rated significantly higher in all characteristics except odor on day 15, although they were rated higher, just not significantly. No difference occurred between treatment III and IV for all sensory characteristics through the entire study.

The efficacy of decontamination treatments using water, sodium hypochlorite, hydrogen peroxide, commercial detergent formulations containing dodecylbenzene sulfonic acid and phosphoric acid, or trisodium phosphate on fresh-cut cantaloupe was determined (Sapers and others, 2001). Microbial population reductions were less than 1 log when plugs were washed with water, 1 to 2 logs with washing and sanitizing agents applied individually, and 3 logs with hydrogen peroxide. The most effective treatment, yielding a shelf life of greater than 2 weeks, was hydrogen peroxide applied at 50 °C.
Calcium chloride dips are another treatment commonly used in the fresh produce industry as a firming agent, the joining of cell wall and middle lamella improved structural integrity (Morris, 1980) and extended shelf life. Fresh-cut cantaloupe was dipped in 2.5% solutions of either calcium chloride at ~25 °C or calcium lactate at ~25 and 60 °C (Luna-Guzman and Barrett, 2000). Calcium chloride and calcium lactate provided significantly firmer samples than water dipped at all dates tested during the 12 day storage. The maintenance of firmness tended to be higher in the calcium lactate treatments. The sensory panel also rated the calcium dipped samples significantly higher in firmness. The panel rated the calcium chloride samples higher in bitterness, but not the calcium lactate samples. All other attributes were not significantly different among samples analyzed. No differences in total plate count were observed between any treatments.

Many variables must be taken into account when processing fresh produce to be stored for later consumption. The sharpness of the blade of the knife used can have an effect on the shelf life and quality of fresh-cut cantaloupe (Portella and Cantwell, 2001). Fresh-cut cantaloupe was prepared using a stainless steel borer with sharp or blunt blades and stored for 12 days in air at 5 °C. Pieces cut with the sharp borer maintained marketable visual quality for at least 6 days and those cut with the blunt borer were considered unacceptable with surface translucency and color changes. Decay, firmness, sugar content and aroma did not differ due to sharpness of borer. Blunt cut pieces had higher ethanol concentrations, off-odor scores, electrolyte leakage and darker orange color with L* and chroma values decreasing significantly during storage. Respiration
rates were not affected for those samples stored at 5 °C, but the blunt pieces stored at 10 °C had a significant increase after day 6.

**Flavor**

Volatile aroma constituents were assessed immediately after processing and after storage for 24 hrs, 3 days and 7 days at 4 °C in fresh-cut cantaloupe (Lamikanra and Richard, 2002). Aliphatic and aromatic esters were the predominant compounds isolated from the fruit immediately after cutting. Methylbutyl acetate and hexyl acetate were the most prominent compounds, which are typically present in large quantities in cantaloupe (Nussbaumer and Hostettler, 1996; Moshonas and others, 1993). After storage for 24 hrs, a considerable decrease in the concentration of esters occurred and synthesis of terpenoid compounds B-ionone and geranylacetone was detected. After the initial decrease, the volatile aroma compounds remained fairly stable over the 7 day storage. The amount of terpenoid compounds decreased after the first day, but remained stable from day 3 to 7. The reduction of esters, which could be precursors for synthesis of secondary volatile aroma compounds, may be directly related to a decrease of fresh like attributes in fresh-cut cantaloupe during storage.

**Modified Atmosphere Packaging**

Modified atmosphere packaging (MAP) refers to any container used to control the concentration of specific gases in order to achieve levels desirable to content. The goals for MAP of fresh-cut produce are to maintain a lower oxygen and higher carbon dioxide level than that of the surroundings. Reducing respiration rate and extending shelf life are the returns for the added cost of using MAP films.
The design of a MAP appears to be rather simple on the surface, but many considerations must be accounted for. The temperature the produce is going to be held at is important since metabolic activity is very dependent on temperature. Most packages will go from the packinghouse, to a truck, to the point of sale, all with different temperatures. The change in respiration rate due to an increase in temperature is usually greater than the change in permeability of the package (Exama and others, 1993). The package may not be able to get back to equilibrium even once the lower temperature is achieved again, since the product may have used more oxygen than planned and gone into anaerobic respiration.

Respiration rates of horticultural commodities is also dependent on the amount of available oxygen and carbon dioxide present in the surrounding environment (Beaudry, 2000; Watkins, 2000). Determination of the optimal surrounding atmosphere for fresh-cut produce is difficult due to the numerous possible combinations of oxygen and carbon dioxide concentrations. The changes in sensory properties of fresh-cut cantaloupe held at different controlled atmospheres were determined (O’Connor-Shaw and others, 1996). A large experimental design was used with 36 gas combinations and four air treatments. All possible combinations of 3.5, 6, 10.5, 13, 15.5, and 17 percent oxygen with 0, 6, 9.5, 15, 19.5, and 26 percent carbon dioxide were evaluated at 4.5 °C. At 14 day intervals, a trained sensory panel assessed the stored fruit. Three treatments remained acceptable up to 28 days: 6% carbon dioxide and 6% oxygen, 9.5% carbon dioxide and 3.5% oxygen, and 15% carbon dioxide and 6% oxygen. Greatest reductions of quality were in samples held in 0, 19.5 or 26% carbon dioxide. Many other combinations of oxygen and carbon dioxide would have to be tested to finalize an optimal atmosphere.
Internal gas mixtures of modified atmosphere package may be attained naturally, by letting the respiration of the produce decrease oxygen and increase carbon dioxide to the desired levels (termed “passive MAP”), or the package may be flushed with the desired gas mixture (active MAP). In a study by Bai and others (2001), fresh-cut cantaloupe was placed in film sealed containers, stored at 5 °C and allowed to attain an internal gas atmosphere naturally (nMAP) or flushed with 4 kPa oxygen and 10 kPa carbon dioxide (fMAP) and another group was maintained near atmospheric levels by perforating the film (PFP). The oxygen and carbon dioxide levels in the PFP remained similar to the ambient air until day 9 and then only changed by 1 to 2 kPa during the next 3 days. Using a flow through system to simulate the atmosphere within the PFP, the oxygen uptake was stable until day 5 at which point it increased more than sixfold during the next 7 days. Neither oxygen or carbon dioxide reached an equilibrium in the nMAP, with the oxygen concentration decreasing to 8 kPa and the carbon dioxide increasing to 12 kPa during the 12 day storage. Respiration rate remained stable through day 9 and then increased twofold by day 12. In the fMAP, the gas mixture remained essentially unchanged at 4 kPa oxygen and 10 kPa carbon dioxide. Respiration rate was also stable in the fMAP for the duration of 12 days. The ethylene accumulation of the fMAP was ¼ of that of the nMAP. Visual quality and aroma were rated acceptable for 12 days for the nMAP and fMAP, whereas the PFP was only acceptable for an average of 6 days. Translucency was significant 2 days earlier in the nMAP and was two to fivefold higher between 9 and 12 days compared to the fMAP. Total microbial population was 1 log lower in both nMAP and fMAP compared to PFP. Yeast and mold populations were around 2 logs lower for both nMAP and fMAP. Therefore, rapidly flushed active MAP
(4 kPa oxygen and 10 kPa carbon dioxide) maintained better quality, had better color retention and reduced translucency, respiration rate, and microbial population compared to an air control (perforated film) and passive MAP (naturally obtained equilibrium).

Respiration rate of fresh-cut apple slices was reduced by increasing carbon dioxide partial pressures from 0 to 30 kPa at 0.5, 1 and 10 kPa oxygen during storage (Gunes and others, 2001a). Carbon dioxide production was not affected during the first week of storage. By week 2 and 3, respiration rate decreased as carbon dioxide partial pressure increased and oxygen partial pressure decreased. Elevated levels of carbon dioxide reduced respiration rate by inhibiting succinate dehydrogenase and other enzymes of the TCA cycle with an indirect effect on oxidative phosphorylation and a direct effect on mitochondrial activity (Mathooko, 1996). The elevated carbon dioxide also reduced browning to a limited extent.

The question of whether an optimal controlled atmosphere for fresh-cut produce can really be found was reviewed extensively in a paper by Saltveit, (2003). A truly optimal atmosphere may be impossible to find due to the natural variability in the raw material and its dynamic response to processing and storage conditions. The best approximations for an optimal modified atmosphere are derived from empirical observations from experimentation including a variety of temperature, relative humidity, oxygen, carbon dioxide, ethylene and duration conditions during storage. Since these variables are usually held constant for the duration of the static experiment, the variability and dynamic response of the commodity to changes in storage environment may be overlooked. Many other variables may affect the environment such as microbial load, light, orientation of the product in the gravitational field and the concentration of other
gases. The optimal modified atmosphere for some quality parameters can be mutually exclusive during storage. Mold control, reduction of ethylene effects and reduction of chlorophyll loss are benefits of high carbon dioxide levels. Increased anaerobic respiration and phenolic metabolism may also result from high carbon dioxide levels. Although low oxygen levels may reduce respiration and ethylene synthesis, it also increases the chance of anaerobic respiration, off flavor production and growth of anaerobic microorganisms.

The optimal storage atmosphere must be defined by the company responsible for the sale of the commodity. The goal is to produce the best quality product, which allows for subjective and objective measures. People perceive cantaloupe in different ways, therefore there are likely to be differences in description about a “perfect” cantaloupe. Some may prefer a darker orange color and softer texture and others may prefer a lighter orange color and firmer texture. Different cultivars, seasons and market segments make a strict universal description of quality very difficult to construe. Some quality aspects may be sacrificed for others along with those which jeopardize shelf life. Which market segment does a company package for and what quality parameters are the most important? These are the questions that must be answered in package design and are most likely answered by cost analysis and return on investment. A mathematical model that incorporates the dynamic response of the produce to the storage environment may be necessary for the optimal modified atmosphere design of a package.

The following Figures (2.1 and 2.2) show ranges of recommended oxygen and carbon dioxide levels for storage of produce (Saltveit, 2003). These ranges can be used
as guidelines for designing a modified atmosphere package. The recommended range for fresh-cut cantaloupe is 3 - 5% oxygen and 5 - 15% carbon dioxide (Gorny, 2001).

Figure 2.1. Recommended oxygen and carbon dioxide ranges for the storage of some harvested vegetable commodities (Saltveit, 2003).
Figure 2.2. Recommended oxygen and carbon dioxide ranges for the storage of few harvested vegetable commodities showing differences within individual commodities (Saltveit, 2003).

Figure 2.2 shows differences in recommended oxygen and carbon dioxide levels for storage within individual commodities. Differences within commodities tightens the range of atmospheres, enhancing the degree of difficulty in designing an optimal atmosphere for MAP.

**Modeling**

Predictive modeling in modified atmosphere packages of fresh-cut produce is centered around the permeance of the film and the respiration rate of the product. Determination of the amount of oxygen diffusing through a modified atmosphere package can be determined using Fick’s first law of diffusion (Zhu and others, 2002):

\[
J_{O_2} = \frac{P_{O_2}}{X} \cdot A(\text{pO}_2 \text{out} - \text{pO}_2 \text{in})
\]  

(2.9)
where $J_{O_2}$ is the rate of diffusion of oxygen through the film in unit time (ml (STP)/hr), $P_{O_2}$ is oxygen permeability coefficient of the film (ml (STP)/m hr kPa), $A$ is the total film surface area (m$^2$), and $X$ is the thickness of the film (m). $p_{O_2}{in}$ is the oxygen partial pressure (kPa) inside the package and $p_{O_2}{out}$ is the oxygen partial pressure (kPa) outside the package. A similar equation can be used for the rate of diffusion for carbon dioxide:

$$J_{CO_2} = \frac{P_{CO_2}}{X} * A(p_{CO_2}{in} - p_{CO_2}{out}) \quad (2.10)$$

where $J_{CO_2}$ is the rate of diffusion of carbon dioxide through the film in unit time (ml (STP)/hr), $P_{CO_2}$ is carbon dioxide permeability coefficient of the film (ml (STP)/m hr kPa), $A$ is the total film surface area (m$^2$), and $X$ is the thickness of the film (m). $p_{CO_2}{in}$ is the carbon dioxide partial pressure (kPa) inside the package and $p_{CO_2}{out}$ is the carbon dioxide partial pressure (kPa) outside the package. According to these equations, the $J_{O_2}$ and $J_{CO_2}$ would both be positive under normal atmospheric conditions, around 21% oxygen and 0% carbon dioxide. Therefore, these equations are for typical conditions and attention must be paid if the surrounding environment or flush gas causes a negative to result in the $(p_{O_2}{out} - p_{O_2}{in})$ or $(p_{CO_2}{in} - p_{CO_2}{out})$ part of the equation.

Respiration rate of the product must be written in equation form to use for modeling. Most empirical models are for a specific temperature with the controllable variables being the oxygen and carbon dioxide concentrations. Many different models are presented in the literature: linear (Henig and Gilbert, 1975; Fishman and others, 1996; Lakalul and others, 1999), polynomial (Yang and Chinnan, 1988; Gong and Corey, 1994), exponential (Cameron and others, 1989; Edmond and others, 1993), and many Michaelis-Menten type equations (Lee and others, 1991; Haggar and others, 1992;
Talasila and others, 1994). A typical respiration rate equation will have the units ml or mg of oxygen or carbon dioxide per kg of produce per unit of time. Therefore, the oxygen consumption rate of produce in a package can be expressed by Eqn. (2.11).

\[ Q_{O_2} = W \times R_{O_2} \]  

(2.11)

Where \( Q_{O_2} \) is the oxygen consumption rate with units ml (STP)/h and \( W \) is the weight of the produce in the same mass unit used in the respiration equation. Similarly, the carbon dioxide production rate of produce in a package can be expressed by Eqn. (2.12).

\[ Q_{CO_2} = W \times R_{CO_2} \]  

(2.12)

Where \( Q_{CO_2} \) is the carbon dioxide production rate with units ml (STP)/h and \( W \) is the weight of the produce in the same mass unit used in the respiration equation. To predict the gas compositions inside a package a stepwise integration can be performed with Eqns. (2.13 and 2.14) (Hayakawa and others, 1975; Zhu and others, 2002).

\[ p_{O_2}(t + \Delta t) = P_{O_2}(t) + (J_{O_2} - Q_{O_2}) \times \frac{P_t(t)}{V} \times \Delta t \]  

(2.13)

\[ p_{CO_2}(t + \Delta t) = P_{CO_2}(t) + (Q_{CO_2} - J_{CO_2}) \times \frac{P_t(t)}{V} \times \Delta t \]  

(2.14)

The \( P_t \) term is expressed in Eqn. (2.15). The total pressure inside a package may not be constant due to the respiratory quotient (RQ; carbon dioxide produced / oxygen consumed) not being unity and with most polymer films the ratio of the carbon dioxide to oxygen transmission rates is at least 2 or 3 to 1. Since nitrogen is neither used nor produced it can be assumed that the number of moles is constant and the total internal pressure at \( t \) can be calculated with the following equation (Moyls and others, 1992):
\[(Pt)_{t} = \frac{\%N_{2o}}{\%N_{2}t} \times 101.303 \quad (2.15)\]

where \(\%N_{2o}\) is the percent of nitrogen in the surrounding atmosphere outside of the bag and \(\%N_{2}t\) is the percent of nitrogen inside the bag at time \(t\).

Using Eqns. (2.13 and 2.14), the internal gas composition at any time during the storage can be determined. An optimal package can be designed by adjusting the weight of the produce, choosing the best available film and amount of surface area, determining and flushing with the best gas composition and the amount of free volume as well as the optimal storage temperature.

**Michaelis-Menten**

The concept of enzyme kinetics being used for predictive modeling of the respiration rate of produce was introduced by Yang and Chinnan (1988). Lee and others (1991) suggested that a Michaelis-Menten type equation might work since respiration is controlled by enzymatic reactions catalyzed by allosteric enzymes and governed by feedback inhibition (Solomos, 1983). They also speculated that since the Michaelis-Menten equation is used to describe the respiration rate of microorganisms and that fresh produce respiration and microorganism respiration are similar, that it could be used for produce. In an atmosphere void of carbon dioxide, the respiration rate dependent on oxygen concentration can be determined with Eqn. (2.16).

\[R = \frac{Vm[O_2]}{Km+[O_2]} \quad (2.16)\]

\(V_m\) is the maximum respiration rate with units mL/kg hr or mg/kg hr, \([O_2]\) is the oxygen concentration in percentage, \(K_m\) is the Michaelis-Menten constant in percent oxygen.
The equation for the respiration rate with an uncompetitive inhibition mechanism due to carbon dioxide is expressed in Eqn. (2.17).

\[
R = \frac{V_m [O_2]}{K_m + (1 + \frac{[CO_2]}{K_i})[O_2]}
\]  \hspace{1cm} (2.17)

\(V_m, K_m\) and \([O_2]\) are the same as above and \([CO_2]\) is the carbon dioxide concentration in percentage and \(K_i\) is the inhibition constant in percent carbon dioxide.

Functionality of (Eqn. 2.17) is dependent on sufficient oxygen concentration for aerobic respiration (Lee and others, 1991).

To test the validity of these equations for use as a respiration model, published data was evaluated by Lee and others (1991). Eqn. (2.16) was linearized to become Eqn. (2.18).

\[
\frac{[O_2]}{r} = \frac{K_m}{V_m} + \frac{[O_2]}{V_m} \hspace{1cm} (2.18)
\]

The data were fit and a Haynes plot was preferred over the Lineweaver-Burk plot due to a more even distribution of error. Most of the data showed high linearity with coefficients of determination \((R^2)\) above 0.95. With the exclusion of one set of published data, the Michealis-Menten equation was concluded to express dependence of respiration rate on oxygen quite well.

Eqn. (2.17) was linearized as Eqn. (2.19) to examine the effects of carbon dioxide on respiration rate.

\[
\frac{1}{r} = \frac{1}{V_m} + \frac{K_m}{V_m} * \frac{1}{[O_2]} + \frac{1}{K_i * V_m} * [CO_2] \hspace{1cm} (2.19)
\]

Published data show high linearity for Eqn. (2.19) as well, with all coefficients of determination above 0.92. This equation was determined to be valid up to the carbon
dioxide tolerance limit of the produce. High levels of carbon dioxide may cause an increase in anaerobic respiration. The respiratory quotient may change during anaerobic respiration along with the normal controlling effect on respiration rate of the oxygen and carbon dioxide concentrations.

Lee and others (1991) also tested the Michaelis-Menten model with fresh-cut broccoli. The model was confirmed as successful based on the high linearity of the data on a Hanes plot and a small standard deviation of the respiration rate. A modified atmosphere package was designed and tested. The gas composition in the package agreed very well with predicted oxygen and carbon dioxide concentrations. The model proved to only work well when the oxygen level was high enough for aerobic respiration.

Hagger and others (1992) developed an enzyme kinetics based respiration model, along with the closed system method for generating respiration rates of fresh produce as a function of oxygen and carbon dioxide concentrations. Four temperatures were tested and model parameters for Eqn. (2.17) were estimated with coefficients of determination all above 0.98. Respiration rates could be predicted at any concentration of oxygen and carbon dioxide. The model was tested with a permeable package and the values obtained at 13 °C. The experimental and predicted gas concentrations were in good agreement. Equilibrium was not reached inside the package due to the high respiration rate of cut broccoli and the low oxygen and carbon dioxide permeabilities of the LDPE film used. Anaerobic respiration took over as the oxygen concentration approached zero.

Jacxsens and others (2000) attempted to design MAPs for fresh-cut vegetables subjected to temperature changes. Respiration rate was described by four Michaelis-Menten type equations. The equations were uninhibited, in the absence of CO₂, and the
three possible types of inhibition were competitive, uncompetitive, and noncompetitive. All four equations gave similar results in their experimentation considering CO₂ levels never exceeded 10-15%. Only the inhibiting effect of a decreased O₂ level on respiration rate was taken into consideration. High R² values for the Michaelis-Menten coefficients Vₘₐₓ and Kₘ were determined, although overestimation of O₂ levels inside equilibrium modified atmosphere packages was common among fresh-cut produce tested.

**Irradiation**

A brief description of the history of food irradiation in the USA was summarized from Rosenthal (1992). In the early 1920’s, irradiation was used to kill the human parasite *Trichinella spiralis* in pork. In the 1940’s, large quantities of radioisotopes became readily available at low cost due to the advent of many nuclear reactors. Van de Graaff generators and linear accelerators, which produce high-energy electron beams also became available at the same time. The study of food irradiation began at Massachusetts Institute of Technology under the guidance of Prof. B. E. Proctor and spread to laboratories around the world after World War II. Most studies in the United States were aimed at sterilizing food. It was determined that doses up to 50 kGy were needed to eliminate heat resistant spores such as *Chlostridium botulinum*. However, this high dose caused unacceptable change in flavor and color, and the difficulty of finding participants for testing the wholesomeness of irradiated foods led to the decline in interest in irradiation technology. The interest in low-dose irradiation of food was rekindled in the late 1960’s with increased concern of synthetic additives, chemical residues and the prevention of food poisonings. This led to the U.S. Food and Drug Administration (FDA) ruling that ionizing radiation should be treated as a food additive not a food process. This changed in 1986 when the FDA approved the use of ionizing radiation to
inhibit the growth and maturation of fresh foods and to disinfect food of arthropod pests at doses not to exceed 1 kGy (Rosenthal, 1992; Code of Federal Regulations, 2004).

The U.S. Code of Federal Regulations outlines the uses of ionizing radiation for the treatment of foods (Code of Federal Regulations, 2004). Energy sources are limited to gamma rays from sealed units of radionuclides Cobalt-60 and Cesium-137, electrons and x-rays generated from machine sources at energies not to exceed 10 and 5 million electron volts, respectively. According to U.S. law, foods treated with irradiation shall bear the logo (Figure 2.3); known as the radura, along with the following statement “Treated with radiation” or “Treated by irradiation” in addition to information required by other regulations.

Figure 2.3. The radura symbol, which is required by U.S. law to be in plain sight on all packages of irradiated foods.
Climacteric fruit ripening may be stimulated or delayed by low-dose irradiation. Skin browning or scalding, internal browning and increased sensitivity to chilling injury are possible post irradiation problems. Pectins, cellulose, hemicellulose and starch may be depolymerized in response to irradiation, which may cause softening. There is a paucity of knowledge of the biochemical mechanisms underlying the delay in senescence of climacteric fruits by irradiation. Many hormonal and cellular changes occur during the ripening process and an accurate relationship with irradiation has not been established (Thomas 1985; Rosenthal 1992).

Minea and others (1996) irradiated strawberries, cherries, sour cherries, apricots, nectarines and apples with an electron beam using a linear electron accelerator at doses between 0.1 and 3 kGy. A shelf-life extension was achieved for all irradiated fruit ranging from 4-8 days. No significant changes in soluble solids content (Brix), total sugars, reducing sugars, pH value and conductivity were observed in irradiated fruit compared to non-irradiated. An average 10% loss of vitamin C occurred in irradiated samples. The most efficient doses with respect to shelf-life extension were determined to be: 2-3 kGy for strawberries, 1 kGy for cherries, 0.5-1 kGy for sour cherries, 0.5-0.7 kGy for apricots, 1-2 kGy for nectarines and 0.5 kGy for apples. Irradiation was reported to have no effect on organoleptic properties for all fruits tested, although on most storage dates irradiated fruits rated 2-3 increments higher in acceptability than non-irradiated on a 1-5 scale.

Lu and others (In Press) irradiated fresh-cut celery at 0.5, 1.0 or 1.5 kGy using a gamma source. Microbial populations decreased with an increase of dose with a 2 log reduction in bacteria and a 1 log reduction in fungi at 1.0 kGy. Bacteria of the E. coli
group were reduced to < 30 mpn (maximum probable number / 100 g) in the 1.0 kGy sample compared to 436 mpn in the non-irradiated controls. Respiration rate and polyphenol oxidase activity were significantly reduced in the 1.0 and 1.5 kGy samples on day 3, 6, and 9. The sensory quality of irradiated celery was better than that of the non-irradiated celery, and the 1.0 kGy sample was the best among irradiated samples.

Chervin and others (1992) examined the reduction of wound-induced respiration by irradiation in fresh-cut and intact carrots stored at 20 °C. The uptake of oxygen in grated carrots was twice that of the intact organs. The respiration rate of intact carrots treated with gamma rays (2 kGy) was observed to be higher than non-irradiated samples at time 0, but after 12 hours the difference disappeared. The non-irradiated grated carrots respiration rate increased more rapidly and peaked higher than the irradiated grated carrots. The consequences of irradiation on the composition of modified atmospheres in plastic bags were also evaluated. Differences occurred in the evolution of gaseous atmospheres in control and irradiated grated carrots. The concentration of carbon dioxide reached 17% after 17 days in non-irradiated samples, but they did not reach 10% in treated samples at 10 °C. The values of the RQ remained stable and close to one throughout the experiment for all samples.

Radiation induced texture changes in produce can be a major limiting factor. Many plant tissues have a threshold level of irradiation dose at which point softening becomes a problem (Massey and Bourke, 1967). Softening in tissues may be due to breakdown of cell wall constituents such as pectin, cellulose and hemicellulose, and alteration of semipermeable membranes resulting in structural weakening and loss of turgor (Kertesz and others, 1964). A threshold of 0.34 kGy was found for fresh-cut apple slices (Gunes
and others, 2001b). Firmness decreased with increased irradiation dose above 0.34 kGy. Dose rate was determined to affect textural response of slices on day 0 with 2 kGy/h resulting in less loss of firmness than 0.4 kGy/h. The effect of dose rate was not significant after 3 and 6 days of storage at 5 °C. Firmness slightly increased over time in samples irradiated at 1 kGy.
CHAPTER 3
EFFECTS OF IRRADIATION ON FRESH-CUT CANTALOUPE STORED IN AN OPEN SYSTEM

Introduction

Fresh-cut produce continues to increase in demand with cantaloupe (*Cucimus melo* L reticulatus) among the most important in terms of volume produced and value (Suslow and others, 2001). The goal of fresh-cut products is to deliver convenience and high quality. Therefore, fresh-cut products must not only be aesthetically pleasing, but also comply with food safety requirements. Consumers expect fresh-cut products to be without defects, of optimum maturity, fresh appearance, and have high sensory and nutrient quality (Watada and Qi, 1999). Fresh-cuts are usually more perishable and unstable than the original products, due to extreme physical stresses from processes such as peeling, cutting, slicing, shredding, trimming, coring, and removal of protective epidermal cells (Watada and others, 1996). A 10 day shelf life of fresh-cut melons is desirable in the distribution chain, but marketing in retail stores usually does not exceed 3 day (Bai and others, 2001). Extension of shelf life while maintaining salable quality would be advantageous to producers and consumers.

Quality of fresh-cut produce is directly related to wounding associated with processing. Physical wounding and damage also induces additional deleterious physiological changes within produce (Brecht and others, 2004; Saltveit, 1997). Symptoms can be visual, such as deterioration from flaccidity with water loss, changes in color, especially browning at the surfaces, and microbial contamination (Brecht, 1995;
King and Bolin, 1989; Varaquaux and Wiley, 1994). Wounding also leads to reduction in flavor and aroma volatile production (Moretti and others, 2002).

One of the first responses to wounding is a transient increase in ethylene production and an enhanced rate of respiration. Increased respiration can lead to excessive losses of nutrients (Brecht, 1995). Ethylene can also stimulate other physiological processes, causing accelerated membrane deterioration, loss of vitamin C and chlorophyll, abscission, toughening, and undesirable flavor changes in many horticultural products (Kader, 1985). Wounding also allows for easier attack and survival of plant pathogenic microorganisms and food poisoning microorganisms.

Radiation research directed towards the preservation of foods began in 1945 (Karel, 1975). Food irradiation generally refers to the use of gamma rays from radionuclides such as $^{60}$Co or $^{137}$Cs, or high-energy electrons and X-rays produced by machine sources to treat foods. Using good manufacturing practices, irradiated foods have been established to be safe, wholesome and without residues (Farkas, 1998). Two major benefits of irradiation are that a product can be treated in its final package as a terminal treatment (Farkas, 1998), and the temperature of the product is not significantly affected. In a paper by Minea and others (1996), strawberries, cherries, apricots, and apples were irradiated with an electron accelerator at doses ranging from 0.1 to 3 kGy at dose rates from 100 to 1500 Gy/min. Results showed irradiation was very effective by way of microbial destruction and had a great influence in decreasing enzymatic activities. Shelf life extension of at least 4 to 7 days was achieved with organoleptic properties not significantly affected. There were no significant changes in the physical and chemical properties of the irradiated fruit.
To be labeled fresh-cut, fruit tissue must be living and therefore respiring (Gorny, 2000). Respiration involves the consumption of oxygen and production of carbon dioxide and water. Inhibition of respiration and ethylene production, which slows deteriorative changes of senescence, generally extends shelf life (O’Connor-Shaw and others, 1996). Therefore, decreasing respiration rate without complete inhibition would be beneficial to produce to be labeled and sold as fresh-cut.

The purpose of this research was to determine the effects of different doses of electron beam irradiation on fresh-cut cantaloupe considering respiration rates, microbiology, texture and color.

**Materials and Methods**

**Fruit Sample**

Cantaloupes (*Cucimus melo* Linnaeus, cv. Athena) were purchased from a retail market in Gainesville, FL (Trial 1 and Trial 2) or obtained from a regional supermarket distribution center (Trial 3). Cantaloupes were transferred to the University of Florida Food Science and Human Nutrition building via automobile and were stored at 25 °C for 1 day and then placed in a 3 °C storage room overnight before processing. Cantaloupes were picked at three quarter to full slip (commercial maturity, when a clear separation from the vine occurs with light pressure) and ready to eat.

**Processing**

Cantaloupes were rinsed in 100 ppm chlorinated water and allowed to dry for 1 hour before cutting. All knives, cutting boards and bowls were soaked with 100 ppm chlorinated water. For each experiment, cantaloupes (12) were halved, de-seeded, and then halved again, resulting in four equal parts. Each quarter was sliced on a ½ HP commercial deli slicer (Model 1712E, Hobart Corporation, Troy, Ohio) with the blade set
at 2.5 cm thick. Slices were then peeled and cut into approximately 2.5 cm pieces with a sharp knife. All pieces were placed in an aluminum bowl, which was surrounded with ice. Pieces were thoroughly mixed to assure random sampling.

Pieces (~300g) were placed in quart Ziploc (S.C. Johnson & Son, Inc., Racine, WI) Freezer bags and sealed after expulsion of most of the air. Bags were placed in ice in a portable cooler and transported to the electron beam irradiation facility, which was a 90 mega amp, 95% scan (Florida Accelerator Services and Technology, Gainesville, FL). Plastic trays were previously frozen with 1.5 cm of ice in them. Bags (4) were taped to each tray with cantaloupe arranged in a single flat layer in order for all pieces to receive equal dosage (Figure 3.1). Dosimeters were also attached to verify that target doses had been reached. The irradiator conveyor was set at a speed of 10 feet per minute (fpm; 305 cm per minute) and 0.25 kGy per pass. To achieve 0.5 kGy, the sample was passed through twice, while for 0.75 kGy three times and so on. Bags were removed from the

Figure 3.1. Schematic of cantaloupe being irradiated in Ziploc bags on trays of ice.
ice trays and placed back in the ice cooler after the desired number of passes. Samples were irradiated at 0, 0.25, 0.5, 0.75, 1.0, 1.25 or 1.5 kGy for Trial 1.

The pieces (~300g) from each bag were then placed in 1-quart Ball Mason Jars (Alltrista Corporation, Indianapolis, IN). Jars and lids were sanitized with a Better Built Turbomatic washer and dryer. Lids were drilled with a 3/8” (0.95 cm) hole directly in the middle. Parafilm (American National Can, Menasha, WI) was wrapped around the top of the jar before attaching the lid to assure a gas-tight seal. Jars containing fresh-cut cantaloupe were stored at 3 °C for the duration of the experiment. Further testing was performed on 1, 3, 5, 7, 9, 12, 14, 16 and 18 d.

Trial 2 was carried out exactly as above except the irradiator was set at 0.1 kGy per pass. Samples were irradiated at 0, 0.1, 0.2, 0.3, 0.4, 0.5 or 0.7 kGy. Further testing was done on 1, 4, 6, 8, 11, 13, 17, and 20 d.

Trial 3 was carried out exactly as above except the irradiator was set at 0.3 kGy per pass. Samples were irradiated at 0, 0.3, 0.6, or 0.9 kGy. Further testing was done on 0, 2, 4, 7, 10, 13, and 16 d.

**Dosimetry**

Radiographic dosimeters were placed under bags of cantaloupe, flat on the trays and on top of bags. Gafchromic MD-55 from International Specialty Products (Wayne, NJ, USA) were cut into 1x1 cm squares, placed in small envelopes and taped into place. The dosimeter film was exposed for 24 hrs and then read on a spectrophotometer at a wavelength of 510 nm. The per pass average was determined by averaging the dose received on top of the bag with that below the bag.
Gas Analysis

Headspace analysis was done by sampling gas composition of jars for contents of O₂ and CO₂ using an O₂ and CO₂ analyzer (Checkmate 9900, PBI-Dansensor, Ringsted, Denmark). Lids were sealed for 2 hrs before sampling with rubber serum stoppers and reopened immediately after gas withdrawal. The sampling needle was pushed through the rubber serum stopper and allowed to take several readings and stabilize. Samples were taken at 3 °C.

Microbial Analysis

Cantaloupe pieces (~20 g) were aseptically removed from the jars and placed in sterile stomacher bags. Samples were diluted 1:10 with phosphate buffer and stomached for 30 seconds. Further 1:10 dilutions were carried out by adding 1 ml of sample to 9 ml of phosphate buffer (1:800, pH 7.2) in dilution tubes and vortexing for 30 seconds. Aerobic Plate Count and Yeast and Mold Plate Count Petrifilm kits (3M Corporation, St Paul, MN) were used as described by instructions for all dilutions tested. Petrifilms were incubated at 25°C for 4 days until quantified.

Color Analysis

Cantaloupe pieces were aseptically removed from jars and placed on Styrofoam plates. In Trial 2, the samples were placed in the Color Machine Vision System consisting of light box and a CCD color camera connected to a computer with a frame grabber along with an orange reference plate with L*, a* and b* values of 24.2, 19.7, and 5.4, respectively. The L* refers to brightness from 0 = black to 100 = white. The a* is from negative (green) to positive (red) and b* is from negative (blue) to positive (yellow). Images were taken of three sides of the sample and saved on the computer. The black frame of the reference plate was removed using Corel for Paint. The image
was then analyzed using the software Color Expert Color Analysis of the system. All images were calibrated with the reference plate. Hue, which is the quality of color and described by the words red, yellow, green, blue, etc., was calculated with the equation \[ \text{hue} = \arctan \left( \frac{b}{a} \right) \]. Chroma, the quality which describes the extent to which a color differs from gray of the same value or lightness, was calculated with the equation \[ \text{chroma} = \left( a^2 + b^2 \right)^{1/2} \] (Billmeyer and Saltzman, 1966).

In Trial 3, the color of the pieces was measured using a hand held Minolta Chroma Meter CR-2006 (Minolta Camera Co., Osaka, Japan). The colorimeter was calibrated before each use with a standard white plate D65 (Y = 94.4, x = 0.3158 and y = 0.3334). One side of each cube was placed flush against the light source and the L*, a*, b* values were measured.

**Texture**

The texture of the cantaloupe was measured by an Instron Universal Testing Instrument, model 4411 (Canton, MA). The six pieces that were analyzed for color were used for texture. The cantaloupe pieces were placed under a plunger, establishing zero force contact, with a plunger diameter of 5.0 mm and compressed 3 mm with a 50 kg load cell. The plunger was driven into the piece with a crosshead speed of 30 mm/min. The maximum compression force was measured in kg.

**Statistical Analysis**

Data was analyzed using analysis of variance in The SAS System version 8e. The empirical model was determined best fit (lowest p-value) after numerous combinations of variables were tested.
Results and Discussion

Respiration

Trial 1

Respiration rates for the fresh-cut cantaloupe of Trial 1 stored at 3°C are shown in Figure 3.2. The respiratory quotient (RQ), defined as the ratio of the volume of CO$_2$ released to the volume of O$_2$ consumed was found to be approximately “unity” for all dates tested. On Day 1, there was a significant difference in all irradiated samples in comparison to the control. All respiration rates (CO$_2$ production) dropped to less than 3.3 ml per kg per hour on Day 3. An effect of irradiation was clearly seen on Day 3 with the higher the irradiation dose the higher the respiration rate. Increased respiration by fruits and vegetables, which may continue for days after exposure, is one of the most readily discerned direct effects of irradiation (Romani, 1966). A similar effect of respiratory activity stimulation by irradiation was observed on different apple cultivars (Massey and others; 1964; Gunes and others, 2000). The respiration rate of the control was significantly greater (p<0.05) than all other treatments after Day 7. The next sample to increase in respiration rate was the lowest irradiation dose, 0.25 kGy. Again, the next sample to increase was the next least irradiated sample of 0.50 kGy. All samples irradiated above 0.50 kGy behaved very similarly throughout storage. The lower respiration rates of irradiated samples has been linked to the reduction of metabolic activity, with the higher the dose, the larger the reduction (Benoit and others, 2000; Ajlouni and others, 1993). Increase in respiration rate after 7 to 9 days of storage at 5 °C for fresh-cut non-irradiated cantaloupe was observed by Aguayo and others (2004). This data is also in agreement with results from Luna-Guzman and Barret (2000), Bai and
others (2001), and Madrid and Cantwell (1993). Possible reasons reported were microbial growth and/or general deterioration of tissue due to senescence.

Figure 3.2. Respiration rate (CO₂ production) of irradiated and non-irradiated fresh-cut cantaloupe stored at 3 °C (Trial 1).

Trials 2 and 3

Respiration rates of fresh-cut cantaloupe for Trial 2, stored at 3 °C are shown in Figure 3.3. The (RQ) was found to be approximately “unity” for all dates tested. Untreated controls had the lowest respiration rates on Day 1 compared to irradiated samples, however, the difference was not statistically significant. Decreases in respiration rates after Day 1 were expected due to recovery from initial cutting for sample preparation. Respiration rates were similar for all samples through Day 8. Statistically significant differences (p<0.05) were observed starting on Day 11, at which point, controls were significantly higher than irradiated samples. Similar results were found with cut iceberg lettuce, where irradiated samples (0.2 and 0.45 kGy) had higher respiration rates on Day 1 and lower on Day 13 (Hagenmaier and Baker, 1997).
Respiration rates observed for Trial 3 (Figure 3.4) were very similar to the Trial 2 results. Headspace analysis was first done at a true time 0. The open system was plugged with the rubber stopper immediately upon placing the cantaloupe in the jars. The initial wound response is more apparent with higher respiration rates observed compared to Day 1 values of other Trials. The respiration rates of the controls significantly increased after day 7 and the irradiated samples did not rise until after day 11. The same effect was seen in which the higher the dose of irradiation the lower the respiration rate for longer over storage time.

![Graph showing respiration rate (CO₂ production) of irradiated and non-irradiated fresh-cut cantaloupe stored at 3 °C (Trial 2).](image)

Figure 3.3. Respiration rate (CO₂ production) of irradiated and non-irradiated fresh-cut cantaloupe stored at 3 °C (Trial 2).

**Microbiology**

Microbiological results for Trial 2 are shown in Figure 3.5. Irradiation was responsible for a 1.5 log reduction in total plate count (TPC) at 0.7 kGy on Day 1. This reduction steadily increased with time, reaching a maximum of 3 logs. Microbial counts of irradiated samples increased at a lower rate than non-irradiated controls, consistent
with the possibility of non-lethal injury to irradiated bacteria as suggested by Welt and others (2001). The TPC for controls and 0.7 kGy samples increased 3.7 and 1.5 logs,
respectively, by Day 11. All samples had TPC levels greater than \(10^8\) at Day 13 except samples treated with 0.4, 0.5, or 0.7 kGy. At Day 17, only samples treated with 0.5 or 0.7 kGy had TPC counts below \(10^8\). The control was significantly higher \((p<0.05)\) than all irradiated samples at days 1, 4, and 13. Irradiation had less affect on the yeast and mold counts, shown in Figure 3.6, with no significant differences among treatments at any

![Figure 3.6](image)

Figure 3.6. Yeast and Molds counts of irradiated and non-irradiated fresh-cut cantaloupe stored at 3 °C (Trial 2).

storage times. The yeast and mold counts of all samples increased approximately 4 logs by Day 17. The TPC counts in Trial 3 were similar to those in Trial 2 (Figure 3.7). The initial 1.5 log reduction of the 0.9 kGy sample only increased to 2.5 logs rather than 3 logs as did the 0.7 kGy sample in the previous study. At all dates, the control was significantly higher than all irradiation levels. In Trial 3, the yeast and mold counts were also similar to those of Trial 2 with a 4 log increase in all samples by day 13 (Figure 3.8).
Figure 3.7. Total plate count (TPC) of irradiated and non-irradiated fresh-cut cantaloupe stored at 3 °C (Trial 3).

At Days 11 and 13 all respiration rates of irradiated samples were significantly lower than controls. Surprisingly, an analysis of covariance failed to uncover a
correlation between microbial populations and observed respiration rates. This suggests that the magnitude of differences in microbial populations did not significantly alter respiration rate results. Additionally, microbial populations on Day 13 for the 0.2 and 0.3 kGy treatments appeared to be higher than those for the control on Day 11, yet observed respiration rates for irradiated samples were significantly lower than those observed for controls. Similar results were found in grated carrots irradiated at 2 kGy and stored at 10 °C in plastic bags. The residual concentrations of oxygen were 2-fold higher in the irradiated samples than in non-irradiated after 7 days of storage. Oxygen consumption was unaffected by microbial contamination (5 to 7 logs cfu/g). The correlation coefficient between the percent residual oxygen and microbial counts was lower than the significant limit of $r = 0.553$ at the 0.05 level (Diem and Seldrup, 1982), indicating the two variables were independent (Chervin and others, 1992).

Based on respiration rates, microbiological bloom and informal sensory evaluations, irradiated samples appeared to maintain preferred quality for 3 to 5 days longer than non-irradiated controls. Respiration rates of the controls increased significantly after Day 8 whereas irradiated samples showed a similar trend only after Day 13.

Equation 3.1 is an empirical model, based on the data of Trial 2, which can be used to estimate respiration rate of fresh-cut cantaloupe as a function of time and irradiation dose.

$$ RCO_2 = 8.819 - 1.856(t) + 6.053(D) - 0.919(t)(D) + 0.135(t)^2 $$(3.1)

where $t$ is the storage time in days, $D$ is irradiation dose level (at $t = 0$) in kGy, and $RCO_2$ is the respiration rate (CO$_2$ production) in ml/kg-hr.
Variables included in Eqn. 3.1 were determined to be statistically significant (p-values < 0.0001). The model provided an overall coefficient of determination $R^2$ of 0.84. This empirical model was based solely on data obtained in this study and is intended to provide a convenient summary of data derived in this work.

**Texture**

The texture of the cantaloupe for Trial 3 is listed in Table 3.1. The texture of the non-irradiated controls was significantly higher than irradiated samples on Day 0; thereafter there were no differences in firmness between irradiated and non-irradiated cantaloupe pieces. This data is similar to diced tomatoes (Prakash and others, 2002), apple slices (Gunes and others, 2001b) and strawberries (Yu and others, 1996) where firmness decreased with increased irradiation. Fruit softening by irradiation was associated with increased water-soluble pectin and decreased oxalate-soluble pectin content. Similar effects were also observed considering the increase of firmness after Day 0 of irradiated cantaloupe pieces.

**Table 3.1. Texture (max force kg) of irradiated and non-irradiated fresh-cut cantaloupe stored at 3 °C (Trial 3). Values in columns with different letters are significantly different (p<0.05).**

<table>
<thead>
<tr>
<th>Texture</th>
<th>Day 0</th>
<th>Day 2</th>
<th>Day 4</th>
<th>Day 7</th>
<th>Day 10</th>
<th>Day 13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0.829 a</td>
<td>0.614 a</td>
<td>0.660 a</td>
<td>0.699 a</td>
<td>0.553 a</td>
<td>0.496 a</td>
</tr>
<tr>
<td>0.3 kGy</td>
<td>0.625 b</td>
<td>0.735 a</td>
<td>0.638 a</td>
<td>0.533 b</td>
<td>0.611 a</td>
<td>0.577 a</td>
</tr>
<tr>
<td>0.6 kGy</td>
<td>0.589 b</td>
<td>0.658 a</td>
<td>0.601 a</td>
<td>0.679 a</td>
<td>0.650 a</td>
<td>0.571 a</td>
</tr>
<tr>
<td>0.9 kGy</td>
<td>0.607 b</td>
<td>0.750 a</td>
<td>0.701 a</td>
<td>0.685 a</td>
<td>0.667 a</td>
<td>0.508 a</td>
</tr>
</tbody>
</table>

The texture of the cantaloupe compared by time within treatments is shown in Table 3.2. The most noticeable and significant decline in firmness was in the controls. The 0.6 kGy sample remained significantly indifferent throughout storage. Boyle and others (1957) reported that threshold ranges of irradiation dose on firmness of apples and carrots depending on cultivar, ranging from ~0.04 to 1.0 kGy.
Table 3.2. Texture (max force kg) of irradiated and non-irradiated fresh-cut cantaloupe stored at 3 °C (Trial 3). Values in columns with different letters are significantly different (p<0.05).

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>0.3 kGy</th>
<th>0.6 kGy</th>
<th>0.9 kGy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 0</td>
<td>0.829 a</td>
<td>0.625 ab</td>
<td>0.589 a</td>
<td>0.607 bc</td>
</tr>
<tr>
<td>Day 2</td>
<td>0.614 bcd</td>
<td>0.735 a</td>
<td>0.658 a</td>
<td>0.750 a</td>
</tr>
<tr>
<td>Day 4</td>
<td>0.660 bcd</td>
<td>0.638 ab</td>
<td>0.601 a</td>
<td>0.701 ab</td>
</tr>
<tr>
<td>Day 7</td>
<td>0.699 b</td>
<td>0.533 b</td>
<td>0.679 a</td>
<td>0.685 ab</td>
</tr>
<tr>
<td>Day 10</td>
<td>0.553 cd</td>
<td>0.611 ab</td>
<td>0.650 a</td>
<td>0.667 ab</td>
</tr>
<tr>
<td>Day 13</td>
<td>0.496 d</td>
<td>0.577 ab</td>
<td>0.571 a</td>
<td>0.508 c</td>
</tr>
</tbody>
</table>

**Color**

The color of all samples remained stable throughout the storage duration for Trial 2 (Table 3.3 and 3.4). The L*, a*, b*, hue, and chroma values varied more from piece to piece and melon to melon than between treatments. No trends in significant differences were found within treatments. Results of the color for Trial 3 were similar to the previous study except after day 7 the controls were significantly lower in L*, a*, b* (Table 3.5) and hue and chroma (Table 3.6). Hue was significantly different on Day 13 only. Chroma was significantly lowest on Day 10 and 13 in the non-irradiated controls. The loss of color may be attributed to the oxidation of B-carotene. No discoloration developed on cantaloupe pieces in any treatment. This absence of browning is the result of a lack of polyphenol oxidase (PPO) enzyme and/or oxidizable phenols in the cantaloupe (Lamikanra and Watson, 2000). Others have reported that hue, chroma and L* values of non-irradiated fresh-cut cantaloupe significantly changed during 25 days of storage at 4 °C (Lamikanra and Watson, 2000). While irradiation had no effect on color in Trial 2, irradiation of fresh-cut cantaloupe in Trial 3 helped maintain color after 8 days of storage. Maintenance of color is very important in the fresh-cut produce industry, where visual appearance on the shelf may be a key factor for extended shelf life purchases.
Differences in L*, a*, and b* values between Trial 2 and Trial 3 may be a result of two reasons. First, the cantaloupes were of different varieties and seasons. The second reason for differences is the method of obtaining color values. The method of Trial 2 involves the use of a digital image that averaged the entire surface of the piece of melon. In Trial 3, the hand held colorimeter only captured a small circle (8 mm$^2$) of the middle of the surface of the melon piece. Therefore, the broad spectrum of colors averaged over the entire surface of cantaloupe (Trial 2) differs from the single point repeatedly measured with the hand held colorimeter (Trial 3).

Table 3.3. Color of irradiated and non-irradiated fresh-cut cantaloupe stored at 3 °C (Trial 2). Values in columns with different letters are significantly different (p<0.05).

<table>
<thead>
<tr>
<th></th>
<th>L</th>
<th></th>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Day 1</td>
<td>Day 4</td>
<td>Day 6</td>
<td>Day 8</td>
<td>Day 11</td>
<td>Day 13</td>
</tr>
<tr>
<td>Control</td>
<td>70.8 a</td>
<td>67.9 a</td>
<td>66.8 ab</td>
<td>68.0 a</td>
<td>65.1 a</td>
<td>65.2 a</td>
</tr>
<tr>
<td>0.1 kGy</td>
<td>71.4 a</td>
<td>68.7 a</td>
<td>68.6 ab</td>
<td>70.3 a</td>
<td>70.7 a</td>
<td>69.0 a</td>
</tr>
<tr>
<td>0.2 kGy</td>
<td>67.5 ab</td>
<td>67.8 a</td>
<td>62.1 b</td>
<td>66.7 a</td>
<td>68.5 a</td>
<td>70.6 a</td>
</tr>
<tr>
<td>0.3 kGy</td>
<td>64.1 b</td>
<td>71.4 a</td>
<td>71.6 a</td>
<td>71.4 a</td>
<td>72.2 a</td>
<td>62.8 a</td>
</tr>
<tr>
<td>0.4 kGy</td>
<td>71.4 a</td>
<td>68.4 a</td>
<td>67.7 ab</td>
<td>67.7 a</td>
<td>68.1 a</td>
<td>70.8 a</td>
</tr>
<tr>
<td>0.5 kGy</td>
<td>67.0 ab</td>
<td>67.1 a</td>
<td>68.3 ab</td>
<td>66.7 a</td>
<td>70.8 a</td>
<td>62.3 a</td>
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<tr>
<td>0.7 kGy</td>
<td>70.2 a</td>
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<td>67.3 ab</td>
<td>64.4 a</td>
<td>67.0 a</td>
<td>68.3 a</td>
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<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td></td>
<td>Day 1</td>
<td>Day 4</td>
<td>Day 6</td>
<td>Day 8</td>
<td>Day 11</td>
<td>Day 13</td>
</tr>
<tr>
<td>Control</td>
<td>28.5 a</td>
<td>36.6 a</td>
<td>27.6 a</td>
<td>20.7 b</td>
<td>24.0 a</td>
<td>30.7 a</td>
</tr>
<tr>
<td>0.1 kGy</td>
<td>29.7 a</td>
<td>34.0 a</td>
<td>26.5 a</td>
<td>23.1 ab</td>
<td>16.7 a</td>
<td>22.3 a</td>
</tr>
<tr>
<td>0.2 kGy</td>
<td>26.5 a</td>
<td>33.6 a</td>
<td>36.0 a</td>
<td>33.5 ab</td>
<td>25.8 a</td>
<td>20.0 a</td>
</tr>
<tr>
<td>0.3 kGy</td>
<td>38.3 a</td>
<td>28.5 a</td>
<td>20.2 a</td>
<td>21.8 b</td>
<td>18.1 a</td>
<td>38.1 a</td>
</tr>
<tr>
<td>0.4 kGy</td>
<td>27.2 a</td>
<td>34.5 a</td>
<td>32.7 a</td>
<td>28.6 ab</td>
<td>28.4 a</td>
<td>23.7 a</td>
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<td>28.4 a</td>
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<td>26.4 a</td>
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<td>41.1 a</td>
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<td>33.3 a</td>
<td>32.6 a</td>
<td>41.6 a</td>
<td>33.7 a</td>
<td>26.1 a</td>
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<table>
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<td></td>
<td>Day 1</td>
<td>Day 4</td>
<td>Day 6</td>
<td>Day 8</td>
<td>Day 11</td>
<td>Day 13</td>
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<td>59.3 ab</td>
<td>58.7 a</td>
<td>55.3 b</td>
<td>57.5 c</td>
</tr>
<tr>
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<td>64.5 a</td>
<td>60.5 ab</td>
<td>61.7 a</td>
<td>60.4 ab</td>
<td>60.0 abc</td>
</tr>
<tr>
<td>0.2 kGy</td>
<td>62.4 ab</td>
<td>62.5 a</td>
<td>57.3 b</td>
<td>61.3 a</td>
<td>61.1 ab</td>
<td>61.5 ab</td>
</tr>
<tr>
<td>0.3 kGy</td>
<td>62.1 ab</td>
<td>64.7 a</td>
<td>62.4 a</td>
<td>63.8 a</td>
<td>63.0 a</td>
<td>57.9 bc</td>
</tr>
<tr>
<td>0.4 kGy</td>
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<td>64.0 a</td>
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<td>61.2 ab</td>
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</tr>
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<td>58.6 bc</td>
</tr>
<tr>
<td>0.7 kGy</td>
<td>58.6 bc</td>
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<td>61.6 ab</td>
<td>61.6 a</td>
<td>61.6 a</td>
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Table 3.4. Hue and chroma of irradiated and non-irradiated fresh-cut cantaloupe stored at 3 °C (Trial 2). Values in columns with different letters are significantly different (p<0.05).

<table>
<thead>
<tr>
<th></th>
<th>Day 1</th>
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<tbody>
<tr>
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<td>69.7 ab</td>
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Table 3.5. Color of irradiated and non-irradiated fresh-cut cantaloupe stored at 3 °C (Trial 3). Values in columns with different letters are significantly different (p<0.05).

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<td>62.4 a</td>
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<td>60.8 a</td>
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<tr>
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<td>54.5 b</td>
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<td>59.7 a</td>
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<table>
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<th>Day 4</th>
<th>Day 7</th>
<th>Day 10</th>
<th>Day 13</th>
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<td>11.3 a</td>
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<td>11.8 a</td>
<td>10.0 a</td>
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<td>0.9 kGy</td>
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<td>31.8 a</td>
<td>29.7 a</td>
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</table>
Table 3.6. Hue and chroma of irradiated and non-irradiated fresh-cut cantaloupe stored at 3 °C (Trial 3). Values in columns with different letters are significantly different (p<0.05).

<table>
<thead>
<tr>
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<th>Day 4</th>
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<th>Day 10</th>
<th>Day 13</th>
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</thead>
<tbody>
<tr>
<td><strong>Hue</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
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<td>70.7 a</td>
<td>70.5 a</td>
<td>73.1 a</td>
<td>74.5 a</td>
</tr>
<tr>
<td>0.3 kGy</td>
<td>70.5 a</td>
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<td>71.2 b</td>
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<td>71.2 b</td>
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<td>70.0 b</td>
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<table>
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<th>Day 4</th>
<th>Day 7</th>
<th>Day 10</th>
<th>Day 13</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chroma</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>0.6 kGy</td>
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<td>37.2 a</td>
<td>33.4 a</td>
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<tr>
<td>0.9 kGy</td>
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<td>35.7 a</td>
<td>32.0 a</td>
<td>37.4 a</td>
<td>33.4 a</td>
<td>31.4 a</td>
</tr>
</tbody>
</table>

Samples removed from jars for color work were used for informal sensory evaluation after being digitally photographed. Four panelists tasted the samples and suggested that there were no substantial differences between the treatments for 8 days. After Day 8, samples treated with higher irradiation dose levels generally had better flavor and texture.

**Conclusions**

Low dose electron beam irradiation of fresh-cut cantaloupe offers promise as a method of maintaining preferred-quality of this product during shelf life. Knowledge of the effects of irradiation on product respiration rates, as summarized in Eqn. 3.1, should provide a means to develop modified atmosphere packaging that could further enhance the ability of irradiation to extend fresh-cut cantaloupe shelf-life.
CHAPTER 4
RESPIRATION OF IRRADIATED FRESH-CUT CANTALOUPE AND MODELLING OF RESPIRATION FOR MODIFIED ATMOSPHERE PACKAGING

Introduction

An effective way to extend the shelf life of fresh produce is to use a modified atmosphere package (MAP). The package should maintain an optimal atmosphere that will reduce respiration and slow physiological and microbiological changes that decrease shelf life. The respiration rate of horticultural commodities is dependent on the amount of available oxygen and carbon dioxide present in the surrounding environment (Beaudry, 2000; Watkins, 2000). Determination of the optimal surrounding atmosphere for fresh-cut produce that minimizes respiration without initiating anaerobiosis or injuring the plant tissue is difficult due to the numerous possible combinations of oxygen and carbon dioxide concentrations.

Determination of respiration rate at different O_2 and CO_2 concentrations is an important factor in the design of a MAP for fresh produce. Generating all the possible combinations of O_2 and CO_2 concentrations using a flow through or flush system in order to determine unique respiration rates would be very time consuming. The closed system has been used to generate more rapid results and cover a range of O_2 and CO_2 concentrations (Haggar and others, 1992; Henig and Gilbert, 1975; Yang and Chinnan, 1988; Gong and Corey, 1994; Cameron and others, 1989).

Determination of the amount of O_2 and CO_2 diffusing in and out of a MAP can be determined using Fick’s first law of diffusion (Zhu and others, 2002). The inflow and
outflow of each gas is controlled by the temperature, internal and external gas concentration and transmission rate of the film.

Predictive modeling in MAPs of fresh-cut produce is centered around the respiration rate of the product and the permeation of gases through the film. The amount of fruit, size of permeable packaging, temperature and starting atmosphere can be adjusted for an optimal package with known respiration rate and gas transmission equations.

The objective of this research was to determine the respiration rate of irradiated and non-irradiated fresh-cut cantaloupe in order to develop predictive equations that could be used to design a MAP with a desirable steady state atmosphere.

**Materials and Methods**

**Fruit Sample**

Cantaloupes (*Cucumis melo* Linnaeus, cv. Athena) were purchased from a local grocery store in Gainesville, FL and transferred to the University of Florida Food Science and Human Nutrition building via automobile and were stored in a 3 °C storage room overnight before processing. Cantaloupes were picked at three quarter to full slip (commercial maturity, when a clear separation from the vine occurs with light pressure) and ready to eat.

**Processing**

Cantaloupes were rinsed in 100 ppm chlorinated water and allowed to dry 1 hour before cutting. All knives, cutting boards and bowls were soaked with 100 ppm chlorinated water. Fifteen cantaloupes were halved, deseeded, and then halved again resulting in 4 equal parts. Each quarter was sliced on a ½ HP commercial deli slicer (Model 1712E, Hobart Corporation, Troy, Ohio) with the blade set at 2.5 cm thick.
Slices were then peeled and cut into approximately 2.5 cm pieces with a knife. All pieces were placed in an aluminum bowl, which was surrounded with ice. Pieces were thoroughly mixed to assure random sampling.

Pieces (~300g) were placed in quart Ziploc (S.C. Johnson & Son, Inc., Racine, WI) Freezer bags and sealed after expulsion of most of the air. Bags were placed in ice in a portable cooler and transported to the electron beam irradiation facility, which was a 90 mega amp, 95% scan (Florida Accelerator Services and Technology, Gainesville, FL). Plastic trays were previously frozen with 1.5 cm of ice in them. Four bags were taped to each tray with cantaloupe arranged in a single flat layer in order for all pieces to receive equal dosage. Dosimeters were also attached to verify that target doses had been reached. The irradiator conveyor was set at a speed of 10 feet per minute (fpm; 305 cm per minute) and 0.1 kGy per pass. To achieve 0.2 kGy, the sample was passed through twice, 0.4 kGy four times and so on. Bags were removed from the ice trays and placed back in the ice cooler after the desired number of passes. Samples were irradiated at 0, 0.2, 0.4 or 0.6 kGy.

The pieces (~300g) from each bag were then placed in 1-quart Ball Mason Jars (Alltrista Corporation, Indianapolis, IN). Three jars of each irradiation dose and three controls, which where processed exactly the same without receiving irradiation were tested. Jars and lids were sanitized with a Better Built Turbomatic washer and dryer. Lids were drilled with a 3/8” (0.95 cm) hole directly in the middle. Parafilm (American National Can, Menasha, WI) was wrapped around the top of the jar before attaching the lid to assure a gas-tight seal. Jars containing fresh-cut cantaloupe were stored at 3 °C for the duration of the experiment. Rubber stoppers were placed in the hole in the lid to
create a closed system immediately upon closing the jar. Gas samples were taken every 4 to 12 hours throughout the 14 day storage duration.

**Dosimetry**

Radiographic dosimeters were placed under bags of cantaloupe, flat on the trays and on top of bags. Gafchromic MD-55 from International Specialty Products (Wayne, NJ, USA) were cut into 1x1 cm squares, placed in small envelopes and taped into place. The dosimeter film was exposed for 24 hrs and then read on a spectrophotometer at a wavelength of 510 nm. The per pass average was determined by averaging the dose received on top of the bag with that below the bag.

**Gas Analysis**

Headspace analysis was done by sampling gas composition of jars for contents of O₂ and CO₂ using an O₂ and CO₂ analyzer (Checkmate 9900, PBI-Dansensor, Ringsted, Denmark). The sampling needle was pushed through the rubber stopper and allowed to take several readings and stabilize. Samples were taken in the cold room without moving the jars.

**Modeling**

The O₂ and CO₂ concentrations were fit to equations (4.1) and (4.2) using KalediaGraph 3.5 (Synergy Software, Reading, PA). The following equations were used in a paper by Hagger and others, (1992) to design an enzyme kinetics based respiration model.

\[
\begin{align*}
[O_2] &= 21 - \frac{t}{(A_1 t + B_1)^c_1} \\
[CO_2] &= \frac{t}{(A_2 t + B_2)^c_2}
\end{align*}
\]
The equations were solved for coefficients A, B and C across time (t) in hours and
[O₂] and [CO₂] in percent. At each sampling time, the respiration rates were calculated
by substituting the first derivatives of Eqns. (4.1) and (4.2) into Eqns. (4.5) and (4.6),
respectively. Eqns. (4.3) and (4.4) are the first derivatives of Eqns. (4.1) and (4.2).

\[ \frac{d[O₂]}{dt} = A_1 C_1 (A_1 t + B_1)^{(-1-C_1)} - (A_1 t + B_1)^{-C_1} \]  
(4.3)

\[ \frac{d[CO₂]}{dt} = -A_2 C_2 (A_2 t + B_2)^{(-1-C_2)} + (A_2 t + B_2)^{-C_2} \]  
(4.4)

\[ r_{O₂} = -\frac{d[O₂]}{dt} \left( \frac{M_{O₂} P V}{100 R W T} \right) \]  
(4.5)

\[ r_{CO₂} = \frac{d[CO₂]}{dt} \left( \frac{M_{CO₂} P V}{100 R W T} \right) \]  
(4.6)

\( r_{O₂} \) is the respiration rate in terms of oxygen consumption (mg/kg h), \( r_{CO₂} \) is the
respiration rate in terms of carbon dioxide production, \( M_{O₂} \) and \( M_{CO₂} \) are the molecular
weights of oxygen and carbon dioxide (kg/mole), respectively, P is the pressure inside the
jar (Pa), V is the free volume (ml), R is the universal gas law constant (8.314 J/mol K), W
is the weight of the cantaloupe (kg), and T is the temperature (in degrees Kelvin).

The respiration rates were fit with the O₂ and CO₂ concentrations in the Michaelis-
Menten enzyme model Eqn. (4.7).

\[ r = \frac{V_m [O₂]}{K_m + (1 + [CO₂]/K_i) [O₂]} \]  
(4.7)

\( K_m \) is the Michaelis-Menten constant (% O₂), \( V_m \) is the maximum respiration rate
(mg/kg h) and \( K_i \) is the inhibition constant (% CO₂).

Respirations rates from Eqns. (4.5) and (4.6) were also fit to several exponential
growth curve functions with Eqns. (4.8) and (4.9) fitting with the highest R-value.
Variables $b_1$ and $b_2$ were solved using KalediaGraph 3.5.

Respiration rates from Eqns. (4.5) and (4.6) were also fit to several polynomial functions with Eqns. (4.10) and (4.11) having the highest $R$-value.

\[ r_{O_2} = b_1 \exp(b_2[O_2]) \]  \hspace{1cm} (4.8)

\[ r_{CO_2} = b_1 \exp(b_2[CO_2]) \]  \hspace{1cm} (4.9)

Variables $M_0$, $M_1$ and $M_2$ were solved using KalediaGraph 3.5. All equations were also fit to the respiration data in exclusive ranges of $[O_2]$ and $[CO_2]$ specific to desirable modified atmosphere packaging conditions for fresh-cut cantaloupe: 10 to 3 percent for $[O_2]$ and 18 to 5 percent for $[CO_2]$.

**Film Permeability**

Based on the respiration rates of the fresh-cut cantaloupe at the desired temperature, two multilayer coextruded bags were provided by Cryovac Sealed Air Corporation (Duncan, SC). All properties reported by the manufacturer were determined at 22.8 °C. Further testing was needed to determine oxygen and carbon dioxide transmission rates at 3 °C. The two bags were the PD-961EZ Bag and the PD-900 Bag.

Oxygen transmission rates (OTR) were measured using a Mocon two-cell Oxtran 2/20 (Mocon Controls Inc, Minneapolis, MN). Sample film pieces (100 cm$^2$) were cut using a stainless steel template. The cut pieces were placed on both testing cells of the Oxtran 2/20 with vacuum grease smoothly applied to the outer edge where the seal is created. The film samples were conditioned for one hour to remove traces of oxygen by flushing them with the test gas mixture, 96% nitrogen plus 4% hydrogen. In the testing
chamber, the film creates a barrier between a steady flow (20 ml/min) of 100% oxygen and a steady flow (20 ml/min) of the test gas mixture. The test gas mixture flows to a coulometric oxygen sensor, which detects the oxygen that permeated through the sample film by producing an electrical current directly proportional to the flux of oxygen across the film. The Mocon unit switches testing chambers when the amount of oxygen detected stops changing. Gas transmission rates were determined at 10, 15, 24, 30, and 35°C and 50% relative humidity. Four 100 cm² sections were tested for each film.

Carbon dioxide transmission rates were determined using the same Mocon Oxtran 2/20 unit with a few modifications. Pure carbon dioxide was connected to the oxygen inlet of the Oxtran 2/20. The oxygen sensor was bypassed, and 10 ml samples were taken from the outflow of test gas. Carbon dioxide levels in the carrier gas after permeation through the film were determined using a Fisher Gas Partitioner model 1200 gas chromatograph (GC; Fisher Scientific, Pittsburgh, PA) with a thermal conductivity detector that was equipped with a 1,966 x 3.12 mm 80/100 mesh Porapak column at 60 °C. The detector and injector temperatures were set 90 °C. Eqn. (4.12) was used to convert the %CO₂ reading from the GC into a transmission rate.

$$\text{CO}_2 \text{TR} = \frac{\text{CO}_2 \text{R} \times \text{FR} \times 1440 \text{ min}}{100 \times \text{day} \times \text{A}}$$

(4.12)

Where CO₂TR is the carbon dioxide transmission rate in ml/m²/day, CO₂R is the carbon dioxide reading from the GC in %, FR is the flow rate of the outflow gas in ml/min, and A is area of the film in m².
The Arrhenius method used for OTR determination was used for carbon dioxide transmission rates, except for the use of the gas chromatograph. Gas transmission rates were determined at 10, 15, 24, 30, and 35°C and 50% relative humidity.

The natural log of the OTRs and the carbon dioxide transmission rates were plotted on the y-axis with 1/T (Kelvin) on the x-axis. Linear regression was done with Microsoft Excel 2000 yielding Eqn. (4.13), which in Arrhenius form is Eqn. (4.14) and rearranged as Eqn. (4.15)

\[
y = mx + b \quad \text{(4.13)}
\]

\[
\ln(k) = \ln(k_0) - \frac{E_a}{RT} \quad \text{(4.14)}
\]

\[
k = k_0 \cdot \exp\left\{-\frac{E_a}{RT}\right\} \quad \text{(4.15)}
\]

k is the permeability of the film in ml/m²/day, ko is the permeability coefficient, Ea is the activation energy for the transport of oxygen or carbon dioxide through the film in kJ/mol, R is the universal gas constant and T is the absolute temperature in degrees Kelvin. Transmission rates can be determined at any temperature using any of the Eqns. (4.13) – (4.15).

**Modified Atmosphere Package Design**

A program to predict the changes over time in [O₂] and [CO₂] of the headspace, surrounding a known weight of fresh-cut cantaloupe in a MAP was written in Microsoft Excel 2000 using Visual Basic for Applications. The following code was used.

Option Explicit

Dim PO2 As Double
Dim PCO2 As Double
Dim A As Double
Dim pO2out As Double
Dim pCO2out As Double
Dim pO2in As Double
Dim pCO2in As Double
Dim pN2out As Double
Dim pN2in As Double
Dim W As Double
Dim RO2 As Double
Dim RCO2 As Double
Dim V As Double
Dim Pt As Double
Dim t As Double
Dim QO2 As Double
Dim JO2 As Double
Dim QCO2 As Double
Dim JCO2 As Double
Dim PN2 As Double
Dim JN2 As Double
Dim M1O2 As Double
Dim M2O2 As Double
Dim M3O2 As Double
Dim M1CO2 As Double
Dim M2CO2 As Double
Dim M3CO2 As Double

Public Sub GetInput()

PO2 = Range("IN!C1").Value
PCO2 = Range("IN!C10").Value
PN2 = Range("IN!C15").Value
A = Range("IN!C2").Value
pO2out = Range("IN!C3").Value
pO2in = Range("IN!C4").Value
pCO2out = Range("IN!C11").Value
pCO2in = Range("IN!C12").Value
pN2out = Range("IN!C13").Value
pN2in = Range("IN!C14").Value
W = Range("IN!C5").Value
'RO2 = Range("IN!C6").Value
V = Range("IN!C7").Value
Pt = Range("IN!C8").Value
't = Range("IN!C1").Value
M1O2 = Range("IN!C16").Value
M2O2 = Range("IN!C17").Value

M3O2 = Range("IN!C18").Value
M1CO2 = Range("IN!C19").Value
M2CO2 = Range("IN!C20").Value
M3CO2 = Range("IN!C21").Value

End Sub

Public Sub Main()
    Call GetInput
    Call SimLoop
End Sub

Public Sub SimLoop()
    t = 1
    Do While t < 5000
        RO2 = M1O2 + (M2O2 * pO2in) + (M3O2 * pO2in ^ 2)
        RCO2 = M1CO2 + (M2CO2 * pCO2in) + (M3CO2 * pCO2in ^ 2)
        QO2 = RO2 * W
        QCO2 = RCO2 * W
        JO2 = PO2 * A * (pO2out - pO2in) * 0.01
        JCO2 = PCO2 * A * (pCO2in - pCO2out) * 0.01
        JN2 = PN2 * A * (pN2out - pN2in) * 0.01
        pO2in = pO2in + ((JO2 - QO2) * (100 / V) * 0.1) 't=.1 hardcode
        pCO2in = pCO2in + ((QCO2 - JCO2) * (100 / V) * 0.1) 't=.1 hardcode
        V = ((-QO2 + QCO2 - JCO2 + JO2 + JN2) * 0.1) + V
        Worksheets("Out").Cells(t + 1, 1).Value = t
        Worksheets("Out").Cells(t + 1, 2).Value = pO2in
        Worksheets("Out").Cells(t + 1, 3).Value = pCO2in
        Worksheets("Out").Cells(t + 1, 4).Value = V
        Worksheets("Out").Cells(t + 1, 5).Value = RO2
Worksheets("Out").Cells(t + 1, 6).Value = RCO2

t = t + 1

Loop

End Sub

Figure 4.1. The input screen for all data necessary for the prediction program with variables described and units defined

The model determines the predicted gas composition inside the bag every 6 minutes. The amount of oxygen consumed and carbon dioxide evolved are determined by the respiration rate of the produce at the initial gas levels for time 1. The amount of oxygen and carbon dioxide that passes through the package is based on the area of transmissible film and the concentration of gases inside and outside the package. The
new internal gas composition and volume are then calculated. The program then loops and recalculates based on new gas composition. The program displays the gas concentrations inside the bag and the free volume in graph form. The respiration rates at each time are also listed in table form. Figure (4.1) is the input screen for the program.

Results and Discussion

Modeling

Headspace concentrations of O₂ and CO₂ over time in the closed jars acted as expected with the O₂ dropping close to 5% and CO₂ rising to almost 20% during 14 days of storage. Figure (4.2) shows the averages of the three jars of each treatment. Coefficients A, B and C of Eqns. (4.1) and (4.2) were solved across time t with high correlation for all treatments (Table 4.1).
Figure 4.2. Percent oxygen and carbon dioxide in headspace during closed system storage of irradiated and non-irradiated fresh-cut cantaloupe at 3 °C.

Table 4.1. Coefficients of Eqn. (4.1) and (4.2) describing the changes in oxygen and carbon dioxide concentrations, respectively, over time for irradiated and non-irradiated fresh-cut cantaloupe stored in a closed system at 3 °C.

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>0.2 kGy</th>
<th>0.4 kGy</th>
<th>0.6 kGy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{\text{O}_2}$</td>
<td>0.413</td>
<td>0.261</td>
<td>0.144</td>
<td>0.222</td>
</tr>
<tr>
<td>$B_{\text{O}_2}$</td>
<td>3.403</td>
<td>4.696</td>
<td>3.613</td>
<td>4.827</td>
</tr>
<tr>
<td>$C_{\text{O}_2}$</td>
<td>0.635</td>
<td>0.672</td>
<td>0.768</td>
<td>0.717</td>
</tr>
<tr>
<td>$R_{\text{O}_2}$</td>
<td>0.996</td>
<td>0.999</td>
<td>0.999</td>
<td>0.999</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>0.2 kGy</th>
<th>0.4 kGy</th>
<th>0.6 kGy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{\text{CO}_2}$</td>
<td>0.752</td>
<td>0.466</td>
<td>0.329</td>
<td>0.9615</td>
</tr>
<tr>
<td>$B_{\text{CO}_2}$</td>
<td>0.001214</td>
<td>0.486</td>
<td>0.229</td>
<td>3.03E-06</td>
</tr>
<tr>
<td>$C_{\text{CO}_2}$</td>
<td>0.533</td>
<td>0.586</td>
<td>0.602</td>
<td>0.494</td>
</tr>
<tr>
<td>$R_{\text{CO}_2}$</td>
<td>0.993</td>
<td>0.997</td>
<td>0.998</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Oxygen consumption and carbon dioxide evolution at each sampling time were solved by inserting the results of Eqns. (4.3) and (4.4) into Eqns. (4.5) and (4.6). The
Table 4.2. Coefficients of Michaelis-Menten model Eqn (4.5) and (4.6) for changes in oxygen and carbon dioxide concentrations, respectively, over time for irradiated and non-irradiated fresh-cut cantaloupe stored in a closed system at 3 °C.

<table>
<thead>
<tr>
<th></th>
<th>O₂</th>
<th>CO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0.2 kGy</td>
<td>0.4 kGy</td>
</tr>
<tr>
<td>Vₘ</td>
<td>26.1</td>
<td>465.4</td>
</tr>
<tr>
<td>Kᵢ</td>
<td>0.29</td>
<td>0.002</td>
</tr>
<tr>
<td>R</td>
<td>0.993</td>
<td>0.972</td>
</tr>
</tbody>
</table>

Respiration rates from Eqns. (4.5) and (4.6) were then used to solve the parameters of the Michaelis-Menten Eqn. (4.7), which are listed in Table (4.2). The R values are high suggesting the data fit well. The model looks good until the gas composition inside a permeable package is predicted. Figure (4.3) and (4.4) shows the curve of the respiration rates across time and the models’ predicted respiration rates across time for the control, with irradiated samples behaving similarly.

The critical area of this curve for O₂ consumption is between 3 and 10% and for CO₂ evolution it is between 5 and 18%. The lower the O₂ concentration, the poorer the Michaelis-Menten equation fit. This could be due to the fact that the Michaelis-Menten model is only valid for aerobic respiration (Lee and others, 1991). Peppelenbos and Leven (1996) determined a significant decrease in O₂ consumption in apples and asparagus at CO₂ levels of 10% and above. Therefore in the critical MAP range, this model will not suffice. An active MAP should start and remain at gas compositions within critical ranges for the produce.
Equation (4.7) was used to fit the observed respiration data to the Michaelis-Menten equation. The parameters $V_m$, $K_m$, and $K_i$ were calculated using the observed data. The results were very similar when all data was used, indicating that the critical ranges for Equation (4.7) were effectively the same for all data.

The exponential growth curves of Equations (4.8) and (4.9) were solved using all respiration data in Figure (4.2). The results were very similar to the solutions for Equation (4.7).
Figure 4.4. Michaelis-Menten equation fit to observed respiration data vs. percent carbon dioxide for non-irradiated fresh-cut cantaloupe stored in a closed system at 3 °C.

(4.7). The R values were very high (~0.99), yet in the critical areas for MAP, the predicted respiration rates would be erroneous. Once again, fitting the critical areas only to the curve was ineffective, therefore continuing the search for the equation yielding proper prediction confidence.

The data was then fit to polynomial curves of Eqns. (4.10) and (4.11) with good results. Fitting the critical areas separately yielded excellent results for all treatments as
seen by the controls in Figures (4.5) and (4.6). The parameter values are listed in Table (4.3).

Table 4.3. Coefficients of the polynomial model Eqns. (4.10) and (4.11) for changes in oxygen and carbon dioxide concentrations, respectively, over time for irradiated and non-irradiated fresh-cut cantaloupe stored in a closed system at 3 °C.

<table>
<thead>
<tr>
<th></th>
<th>O2</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control</td>
<td>0.2 kGy</td>
<td>0.4 kGy</td>
<td>0.6 kGy</td>
</tr>
<tr>
<td>M0</td>
<td>1.257</td>
<td>1.1726</td>
<td>1.428</td>
<td>1.5276</td>
</tr>
<tr>
<td>M1</td>
<td>-0.114</td>
<td>-0.2485</td>
<td>-0.3592</td>
<td>-0.37</td>
</tr>
<tr>
<td>M2</td>
<td>0.013</td>
<td>0.027</td>
<td>0.044</td>
<td>0.034</td>
</tr>
<tr>
<td>R</td>
<td>0.994</td>
<td>0.999</td>
<td>0.999</td>
<td>0.999</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>CO2</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control</td>
<td>0.2 kGy</td>
<td>0.4 kGy</td>
<td>0.6 kGy</td>
</tr>
<tr>
<td>M0</td>
<td>3.579</td>
<td>5.73</td>
<td>8.456</td>
<td>9.757</td>
</tr>
<tr>
<td>M1</td>
<td>-0.33</td>
<td>-0.52</td>
<td>-0.649</td>
<td>-1.0329</td>
</tr>
<tr>
<td>M2</td>
<td>0.009</td>
<td>0.014</td>
<td>0.015</td>
<td>0.032</td>
</tr>
<tr>
<td>R</td>
<td>0.994</td>
<td>0.999</td>
<td>0.998</td>
<td>0.985</td>
</tr>
</tbody>
</table>

The respiration rate can be determined at any O2 plus CO2 combination within the ranges solved for by the polynomial equations. This was considered acceptable since the MAP design in the next chapter was planned to use a gas flush with the desired steady state package atmosphere.

It is uncertain why the Michaelis-Menten equation did not fit the data better in the critical areas. Most published research using the Michaelis-Menten equation for modeling produce respiration involved intact fruits and vegetables or produce lightly processed to a lesser extent than the fruit in this work. The pieces of fresh-cut cantaloupe in this experiment were wounded on all sides. The fruit was peeled, seeded by cutting the most inner cavity layer out and then cubed, which leaves no side uncut. This wounding causes an increase in respiration at time 0 compared to the intact fruit. The pieces also are exposed to gases on all sides with an increased surface area. The solubility and
diffusion rates of O₂ and CO₂ would also have been affected. The initial wound response along with exposure to gases on all sides with differing diffusion and solubility rates may not allow the Michaelis-Menten model to be the best choice.

Most work done with the Michaelis-Menten equation has been performed at higher temperatures than the work done for this paper. Also, the most common fresh-cut produce modeled is broccoli (Fonseca and others, 2002). Therefore, published data shows the depletion of oxygen and increase in carbon dioxide at a faster rate, especially...
Figure 4.6. Polynomial equation fit to observed respiration data vs. percent carbon dioxide for within the critical range for non-irradiated fresh-cut cantaloupe stored in a closed system at 3 °C.

later in storage when broccoli enters a climacteric phase of increasing respiration.

Although cantaloupe is also a climacteric crop, the fruit used in this work were already ripe and presumably postclimacteric at the start of the experiments. Cold storage and the naturally low respiration rate of cantaloupe may cause it to be an unsuitable candidate for Michaelis-Menten modeling.

Many limitations exist in prediction modeling of fresh-cut produce. The results of experimentation can be specific to the environmental conditions as well as the variability
in the commodity. The closed system experiment above started and continued through 
O₂ and CO₂ combinations that would not be present in an active MAP. Most closed 
system models predict respiration rates of produces at internal atmosphere different than 
those used in the creation of the model. For example, the internal starting gas 
composition for the MAPs of the next experiment are 4% oxygen and 10% carbon 
dioxide. Therefore, as seen in Figure (4.2), the percent oxygen at the time when the 
carbon dioxide is 10% is not near 4, and similarly the carbon dioxide percent is very high 
when oxygen is low. The above prediction equations give respiration rates from different 
observed data. Inhibitory and/or promotional effects of the other gas concentration, for 
example oxygen when determining carbon dioxide evolution, may be overlooked. 
Although significant results may be obtained from closed system modeling, further 
testing should be carried out with package design.

**Film Permeability**

The oxygen and carbon dioxide transmission rates of the films for the temperatures 
tested are listed in Table (4.4). The Arrhenius relationships between transmission rates 
and temperature are shown in Figure (4.7) and (4.8). The OTRs for PD-900 and PD- 
961EZ at 3°C were determined by extrapolation of the Arrhenius curve to be 657.31 and 
1529.56 ml/m²/day. The carbon dioxide transmission rates for PD-900 and PD-961EZ at 
3°C were similarly determined to be 3434.03 and 8035.77 ml/m²/day. The Arrhenius 
relationship values Ea and ko are listed in Table (4.5).

The activation energy determined for both films was slightly higher in oxygen 
permeability compared to carbon dioxide permeability. Therefore, the oxygen 
concentrations inside the packages will be more easily influenced by temperature
fluctuations during storage compared to the carbon dioxide concentrations (Van de Velde and others, 2002).

Table 4.4. Average oxygen (OTR) and carbon dioxide (CO₂TR) transmission rates at various temperatures for films tested.

<table>
<thead>
<tr>
<th>Temp degree C</th>
<th>PD 900 ml/m²/day</th>
<th>PD 961 EZ ml/m²/day</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OTR</td>
<td>CO₂TR</td>
</tr>
<tr>
<td>10</td>
<td>1036</td>
<td>2393</td>
</tr>
<tr>
<td>15</td>
<td>1398</td>
<td>3159</td>
</tr>
<tr>
<td>24</td>
<td>2290</td>
<td>5121</td>
</tr>
<tr>
<td>30</td>
<td>3200</td>
<td>7095</td>
</tr>
<tr>
<td>35</td>
<td>4216</td>
<td>9415</td>
</tr>
</tbody>
</table>

Figure 4.7. Arrhenius relationship between the natural log of the oxygen transmission rate (O₂TR) in ml/m²/day and temperature for two films tested.

Table 4.5. Arrhenius relationship values Ea and ko for two films tested.

<table>
<thead>
<tr>
<th>Film</th>
<th>ko ml/m²/day</th>
<th>Ea kJ/mol</th>
</tr>
</thead>
<tbody>
<tr>
<td>OTR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PD 900</td>
<td>40.5</td>
<td>3.06E+10</td>
</tr>
<tr>
<td>PD 961 EZ</td>
<td>39.5</td>
<td>4.63E+10</td>
</tr>
<tr>
<td>CO₂TR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PD 900</td>
<td>31.9</td>
<td>9.26E+09</td>
</tr>
<tr>
<td>PD 961 EZ</td>
<td>35.3</td>
<td>1.63E+10</td>
</tr>
</tbody>
</table>
Figure 4.8. Arrhenius relationship between the natural log of the carbon dioxide transmission rate (CO₂TR) in ml/m²/day and temperature for two films tested.

**Conclusion**

The Michaelis-Menten enzyme kinetics equation was not a suitable model for fresh-cut cantaloupe. A polynomial model fit the oxygen consumption and carbon dioxide evolution data very well and, most importantly, the fit was good in the critical oxygen and carbon dioxide concentration ranges desirable for fresh-cut cantaloupe for MAP. An Arrhenius equation accurately predicted the oxygen and carbon dioxide transmission rates of packaging polymers over a range of temperatures. With known prediction equations for respiration rate of produce and transmission rates of packaging films, an optimal MAP can be easily designed.
CHAPTER 5
DESIGN OF MODIFIED ATMOSPHERE PACKAGE FOR IRRADIATED FRESH-CUT CANTALOUPE AND EVALUATION WITH DESCRIPTIVE ANALYSIS SENSORY PANEL

Introduction

Respiration involves the consumption of oxygen and production of carbon dioxide and water. Aerobic respiration can be slowed by limiting available oxygen. However, oxygen must be maintained above a minimum threshold to prevent anaerobic respiration (Knee, 1980). Additionally, increased carbon dioxide concentration has been shown to slow down ripening and respiration rates (Mathooko, 1996). Therefore, an optimal micro atmosphere may be created via modified atmosphere packaging (MAP), where respiration and ethylene production may be reduced as well as many other degradative processes. A MAP can be developed by matching the proper film with the weight and respiration rate of the respiring contents.

Modified atmosphere packages can be designed using predictive equations based on known respiration data. The respiration rate of most produce is dependent on the oxygen and carbon dioxide levels that surround the produce. An ideal package will maintain the desired levels of decreased oxygen and increased carbon dioxide based on the transmission rates of the package and the respiration rate of the produce at the desired storage temperature. Packages can be flushed with the desired steady-state gas composition in order to avoid the duration of relying on the dynamic process. The quicker the produce is at the optimal atmosphere the more effective the package.
A combination of MAP and irradiation may have a synergistic effect on the shelf life of produce. This was demonstrated by Prakash and others (2000) with cut romaine lettuce. Irradiation increased the shelf life of the MAP fresh-cut lettuce compared to the non-irradiated MAP fresh-cut lettuce by reducing the initial microbial load by 1.5 log CFU/g and maintaining a 4 log CFU/g difference on the 18th day of storage.

The first objective of this research was to design a MAP for irradiated and non-irradiated fresh-cut cantaloupe based on polynomial respiration rate prediction equations and known transmission rates of packaging films. The second objective was to determine the validity of the prediction model and the effectiveness of the package with a trained sensory panel and evaluation of color, texture and microbiology.

**Materials and Methods**

**Fruit Sample**

Cantaloupes (*Cucumis melo* Linnaeus, cv. Magellan and Acclaim) were purchased from a local grocery store in Gainesville, FL on March 14 (Trial 1) and March 30, 2004 (Trial 2). Prior to purchase, the cantaloupes purchased on March 14 and March 30 were shipped from Del Monte (Costa Rica) and Del Sol (Costa Rica), respectively, in a 2% oxygen bag and maintained at 3°C. Cantaloupes were transferred to the University of Florida Food Science and Human Nutrition building via automobile and were stored at 25°C for 1 day and then placed in a 3°C storage room overnight before processing. Cantaloupes were picked at three quarter to full slip (commercial maturity, when a clear separation from the vine occurs with light pressure) and ready to eat.

**Processing**

Cantaloupes were rinsed in 100 ppm chlorinated water and allowed to dry 1 hour before cutting. All knives, cutting boards and bowls were soaked with 100 ppm
chlorinated water. Twenty four cantaloupes were halved, deseeded, and then halved again resulting in 4 equal parts. Each part was then halved again resulting in 8 canoe shaped pieces. Slices were then peeled and cut into approximately 2.5 cm pieces with a knife. All pieces were placed in an aluminum bowl, which was surrounded with ice. Pieces were thoroughly mixed to assure random sampling.

Pieces in Trial 1 (~625g) and Trial 2 (~520 g) were placed in Cryovac Sealed Air Corporation (Duncan, South Carolina) polypropylene trays. Trays were placed in Cryovac Sealed Air Corporation PD-900 MAP bags cut to 32 x 28 cm. The MAP bags were placed on a PAC Table Top Vac/Gas Sealer Model No. PVTSG-24 (Packaging Aids Corporation, San Raphael, CA). The equipment settings were Vacuum 4, Flush Gas 9, Seal Time 11, and Cool Time 5. The flush gas was 3.97% oxygen, 10.0% carbon dioxide, and balanced with nitrogen (BOC Gas, Riverton, NJ). The PAC Table Top Vac/Gas Sealer pulls a vacuum and refills the pouch full with the flush gas, then seals and cools before releasing. Bags were placed in ice in portable coolers and transported to the electron beam irradiation facility (Florida Accelerator Services and Technology, Gainesville, FL). Plastic trays were previously frozen with 1.5 cm of ice in them. Four bags were taped to each tray with cantaloupe arranged in a single flat layer in order for all pieces to receive equal dosage. Dosimeters were also attached to verify target dose had been reached. The irradiator was set at 10 fpm and 0.5 kGy per pass. To achieve 1.0 kGy, the sample was passed through twice. Bags were removed from ice trays and placed back in the ice cooler after desired number of passes. Samples were irradiated at 0, 0.5, or 1.0 kGy.
Packages were transferred back to the FSHN building and stored at 3 °C for the duration of the experiment. Further testing was done on 1, 4, 6, 8, 11, 14, 18, and 20 d for Trial 1 and on 1, 4, 6, 11, 15, 18, and 20 d for Trial 2.

A closed system experiment was also run with the same fruit to produce a rapid method for respiration rate prediction equation determination. Pieces (~300g) were also placed in quart Ziploc (S.C. Johnson & Son, Inc., Racine, WI) Freezer bags and sealed after expulsion of most air. The bags were handled in the same way as the modified atmosphere packages above and irradiated at 0.5, or 1.0 kGy.

The pieces (~300g) of each bag were then placed in a 1-quart Ball Mason Jars (Alltrista Corporation, Indianapolis, Indiana). Jars and lids were sanitized with a Better Built Turbomatic washer and dryer. Lids were drilled with a 3/8” hole directly in the middle. Parafilm (American National Can, Menasha, WI) was wrapped around the top of the jar before applying the lid to assure a gas tight seal. Jars were stored at 3 °C for the duration of the experiment. Rubber stoppers were placed in the hole in the lid to create a closed system immediately upon closing the jar. Gas samples were taken every 4 to 12 hours throughout a 14 day storage duration.

Dosimetry

Radiographic dosimeters were placed under bags of cantaloupe, flat on the trays and on top of bags. Gafchromic MD-55 from International Specialty Products (Wayne, NJ, USA) were cut into 1x1 cm squares, placed in small envelopes and taped into place. The dosimeter film was allowed to expose for 24 hrs and then read on a spectrophotometer at a wavelength of 510 nm. The per pass average was determined by averaging the dose received on top of the bag with that below the bag.
Gas Analysis

Headspace analysis was done by sampling gas composition of bags or jars for contents of O₂ and CO₂ using an O₂ and CO₂ analyzer (Checkmate 9900, PBI-Dansensor, Ringsted, Denmark). Septums of 1.3 cm diameter were placed on all bags. Rubber serum stoppers were placed in the hole in the jar lids. The Checkmate sampling needle was inserted through the septum or stopper. The O₂ and CO₂ percentages were recorded when readings stabilized. All gas samples were taken in the cold storage room.

Microbial Analysis

Cantaloupe (~20 g) were aseptically removed from the packages and placed in sterile stomacher bags. Samples were diluted 1:10 with phosphate buffer (1:800, pH 7.2) and stomached for 30 seconds. Further 1:10 dilutions were carried out by adding 1 ml to 9 ml of phosphate buffer in dilution tubes and vortexing for 30 seconds. Aerobic Plate Count and Yeast and Mold Plate Count Petrifilm (3M Corporation, St Paul, MN) were used as described by instructions for all dilutions tested. Petrifilms were incubated at 25 °C for 4 days then quantified.

Sensory

Sensory analysis using descriptive analysis was conducted by sixteen panelists (8 male, 8 female, 21-45 years of age) who were students and staff of the University of Florida, Food Science and Human Nutrition Department. The panelists were trained during four, 1 hour sessions to recognize fresh and stored cantaloupe attributes, a week before the first evaluation. Cantaloupes stored for different times, some vacuum sealed, some exposed to air, some irradiated and fresh cantaloupes were given to panelists during the first training session. The panelists were asked to write down all terms they felt described the different samples. All panelists announced their descriptor terms and
discussed them. All terms were compiled and given to the panelists on the second training date. Samples were analyzed again and through elimination and agreement, the most important terms were finalized: appearance terms- orange and moist; texture terms- firmness, mealy, juicy and crispness; and flavor terms- sweetness, cantaloupe flavor intensity, off-flavor, pumpkin and overall acceptability.

In the third session, the panelists were given a practice ballot and rated the training samples. Each attribute was rated using a 15 cm line scale with anchors at 13 mm from each end, anchored with the terms high and low. Panelists were instructed to mark anywhere on the line to rate the intensity. Panelists discussed their results and agreed that the ballot covered all necessary terms. The panel also decided where typical or common fresh-cut cantaloupe should be rated.

In the fourth session, panelists were given a practice ballot and rated cantaloupe irradiated that day, as well as stored fresh and irradiated samples. Panelists rated samples consistently with one another.

At each test date, panelists evaluated three samples (control, 0.5 kGy and 1.0 kGy). Samples were coded with a three digit random number and served in small plastic cups (2-3 pieces of cantaloupe). The panelists were provided with water and unsalted crackers in a private booth equipped with a monitor, mouse and keyboard. The panelists marked on the open line on the screen to indicate intensity ratings for each attribute. Compusense five release C5R4.6 (Guelph, Ontario, Canada) was used to design and run all sensory tests. All orders of presentation were presented once, then at random. The samples were evaluated again for replication in the same manner after a short break by the panelist.
Color Analysis

Six cantaloupe pieces from each treatment were removed and placed on Styrofoam plates. The color of the pieces was measured using a hand held Minolta Chroma Meter CR-2006 (Minolta Camera Co., Osaka, Japan). The colorimeter was calibrated before each use with a standard white plate (D65 Y = 94.4, x = 0.3158 and y = 0.3334). One side of each cube was placed flush against the light source and the L*, a*, b* values were measured. The L* refers to brightness from 0 = black to 100 = white. The a* is from negative (green) to positive (red) and b* is from negative (blue) to positive (yellow). Hue, the quality of color, which we describe by the words red, yellow, green, blue, etc., was calculated with the equation hue = arctan (b/a). Chroma, the quality describing the extent to which a color differs from gray of the same value or lightness, was calculated with equation chroma = (a^2 + b^2)1/2 (Billmeyer and Saltzman, 1966).

Texture

The texture of the cantaloupe was measured by an Instron Universal Testing Instrument, model 4411 (Canton, Massachusetts). The six pieces that were analyzed for color were used for texture. The cantaloupe pieces were placed under a plunger, establishing zero force contact, with a diameter of 5.0 mm and compressed 3 mm with a 50 kg load cell. The plunger was driven into the piece with a crosshead speed of 30 mm/min. The maximum compression force was measured in kg.

Statistical Analysis

Non-sensory data was analyzed using analysis of variance in The SAS System version 9e. The sensory data were analyzed two ways. In the first analysis, the data from each storage time were analyzed separately by analysis of variance using SAS version 9e.
The model consisted of panelist effect, treatment effect, panelist*treatment interaction, and replication effect.

In the second analysis, all data were analyzed as split plot design using analysis of variance, with panelists as blocks, treatment as subplot, and storage time as whole plot. Means were separated by Duncan’s Multiple Range Test when a significant F value was obtained (p=0.05). All other data (color, texture and micro) were subjected to analysis of variance as a completely randomized design, with the model consisting of treatment effect and storage time effect.

Results and Discussion

MAP Design

The first step in the design of the modified atmosphere package was the choice of the Cryovac PD-900 film over the PD-961 EZ film. Quick analysis revealed that a large amount of fresh-cut cantaloupe would be required to reach an equilibrium (maintenance of desired internal atmosphere) of gases based on the low respiration rate of the fruit and the higher transmission rate of the PD-961EZ film.

The internal atmosphere beginning conditions were chosen to be 4% O₂ and 10% CO₂. These values of oxygen and carbon dioxide are both in the middle of the recommended ranges for storing fresh-cut cantaloupe (Gorny, 2001). This allowed for maximum unpredicted deviation in either direction, especially important for preventing the growth of anaerobic organisms. Ideally, the internal atmosphere of the package would stay very close to the flush gas composition.

With known respiration rates of the irradiated and non-irradiated fruit and transmission rates of the film, the adjustable parameters were the amount of fresh-cut cantaloupe and the surface area of film. A weight of 500 to 650 g of fresh-cut cantaloupe
was considered reasonable for the Cryovac trays provided. Based on the dimensions of the tray, reasonable bag sizes were determined. Adjusting these two variables, a bag size with total area of 0.135 m$^2$ (0.32 m x 0.211 m x 2 sides) and a fruit weight of 625 g gave satisfactory prediction results. One bag design was chosen for all treatments for consistency in experimentation, with O$_2$ and CO$_2$ concentrations varying no more than ±2% in predicted headspace compositions. Figure 5.1 shows the predicted gas compositions over 500 hours or ~21 days for cantaloupe irradiated at 0.4 kGy. The O$_2$ concentration steadily increased to just less than 5.9% and the CO$_2$ concentration rose to just below 10.6% in the first 300 hours and leveled off for the duration.

![Figure 5.1](image.png)

**Figure 5.1.** Predicted oxygen and carbon dioxide partial pressures for 0.4 kGy samples in designed modified atmosphere package with initial gas flush of 4% O$_2$ plus 10% CO$_2$ for Trial 1 stored at 3 °C.
For the second trial, a bag size with total area of 0.13 m$^2$ (0.203 m x 0.32 m x 2 sides) was used with a fruit weight of 520 g, which also gave satisfactory prediction results. Figure 5.2 shows the predicted headspace compositions over 500 hours or ~21 days for cantaloupe irradiated at 0.4 kGy. The O$_2$ concentration steadily increased to just above 5% and the CO$_2$ concentration rose to just above 10% and remained constant for the duration.

Figure 5.2. Predicted oxygen and carbon dioxide partial pressures for 0.4 kGy samples in designed modified atmosphere package with initial gas flush of 4% O$_2$ plus 10% CO$_2$ for Trial 2 stored at 3 °C.

Figures 5.3-5.6 show the %O$_2$ and %CO$_2$ across time for both trials. Lines in between points are presumed patterns of gas behavior and not actual data. On Day 1 of Trial 1, the %O$_2$ was approximately 5.7% for all treatments. Although a strong vacuum
was pulled on the bags and filled with 4% O₂ plus 10% CO₂ gas mixture, a small amount of ambient air remained in the pockets and cavities created by the stacked fruit. The composition of the air that remained was approximately 21% O₂ and 0.0% CO₂, which caused the initial internal atmosphere to be higher than 4% O₂, which is seen in both trials. This also leads to the expectation of the %CO₂ in the fill gas to be slightly diluted. This was seen in Trial 2 but not Trial 1.

![Figure 5.3](image1.png)

Figure 5.3. Actual oxygen partial pressures for all samples in designed modified atmosphere packages for Trial 1 stored at 3 °C.

![Figure 5.4](image2.png)

Figure 5.4. Actual carbon dioxide partial pressures for all samples in designed modified atmosphere packages for Trial 1 stored at 3 °C.
Figure 5.5. Actual oxygen partial pressures for all samples in designed modified atmosphere packages for Trial 2 stored at 3 °C.

Figure 5.6. Actual carbon dioxide partial pressures for all samples in designed modified atmosphere packages for Trial 2 stored at 3 °C.

In Trial 1, the %O₂ remained steady in the control through Day 6 and for the 0.5 kGy and 1.0 kGy through Day 8. The %CO₂ slowly declined through Day 8 for all treatments. The control %O₂ decreased from Day 6 to 11 and then climbed back up to ~6%. The control %O₂ was significantly the lowest on Day 8 and 11 (Table 5.1). The
%CO₂ in the controls increased between Day 8 and Day 14 and was significantly the highest on Day 11 and 14. These results are very similar to the open system results of Chapter 1. A significant increase in respiration rate was seen in the non-irradiated controls before the irradiated samples. The 1.0 kGy sample changed the least of all samples maintaining the lowest respiration rate. The lower respiration rates of irradiated samples are linked to the reduction of metabolic activity, with the higher the dose the larger the reduction (Benoit and others, 2000; Aljouni and others, 1993). Increase in respiration rate after 7-9 days of storage at 5 °C of fresh-cut cantaloupe was observed by Aguayo and others (2004). This data is also in agreement with results from Luna-Guzman and Barret (2000), Bai and others (2001), and Madrid and Cantwell (1993). Possible reasons reported were microbial growth and/or general deterioration of tissue due to senescence.

In Trial 2, all treatments %O₂ behaved very similarly through Day 11 (Table 5.1). The %O₂ in the control dropped while the %O₂ in the irradiated samples increased after Day 8. The %CO₂ remained similar through Day 11 although significantly different on Day 1 through Day 6, it is presumed to be due to a replication effect at each time. The effect of treatment was clearly seen after Day 11, when the consumption of O₂ and evolution of CO₂ was significantly much higher in the controls. Similar results were found with cut iceberg lettuce, where irradiated samples (0.2 and 0.45 kGy) had higher respiration rates on Day 1 and lower on Day 13 (Hagenmaier and Baker, 1997).

Figures 5.7 and 5.8 compare predicted vs. actual internal atmospheres of packages. In Trial 1, the oxygen prediction and experimental data are in good agreement with very
similar values for 8 days. The carbon dioxide predicted slowly rose to just under 11% and the actual level dropped to just under 8%.

Table 5.1. Headspace composition of modified atmosphere packages of irradiated and non-irradiated fresh-cut cantaloupe stored at 3 °C. Means within a column sharing the same letter are not significantly different (p<0.05).

<table>
<thead>
<tr>
<th>Trial 1</th>
<th>%O₂</th>
<th>Day 1</th>
<th>Day 4</th>
<th>Day 6</th>
<th>Day 8</th>
<th>Day 11</th>
<th>Day 14</th>
<th>Day 18</th>
<th>Day 20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>5.7 a</td>
<td>5.5 a</td>
<td>5.4 a</td>
<td>3.9 b</td>
<td>0.1 b</td>
<td>0.7 b</td>
<td>4.4 a</td>
<td>6.1 a</td>
<td></td>
</tr>
<tr>
<td>0.5kGy</td>
<td>5.8 a</td>
<td>5.6 a</td>
<td>5.7 a</td>
<td>5.7 a</td>
<td>3.9 a</td>
<td>1.1 b</td>
<td>3.8 a</td>
<td>5.2 ab</td>
<td></td>
</tr>
<tr>
<td>1.0kGy</td>
<td>5.7 a</td>
<td>5.4 a</td>
<td>5.5 a</td>
<td>5.7 a</td>
<td>4.9 a</td>
<td>2.1 a</td>
<td>3.2 a</td>
<td>4.2 b</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>%CO₂</th>
<th>Day 1</th>
<th>Day 4</th>
<th>Day 6</th>
<th>Day 8</th>
<th>Day 11</th>
<th>Day 14</th>
<th>Day 18</th>
<th>Day 20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>10 a</td>
<td>8.6 b</td>
<td>8.2 a</td>
<td>7.6 a</td>
<td>12 a</td>
<td>14 a</td>
<td>14 a</td>
<td>13 a</td>
</tr>
<tr>
<td>0.5kGy</td>
<td>10 a</td>
<td>8.9 b</td>
<td>8 a</td>
<td>7.7 a</td>
<td>9.1 b</td>
<td>13 b</td>
<td>13 a</td>
<td>13 a</td>
</tr>
<tr>
<td>1.0kGy</td>
<td>10 a</td>
<td>9.3 a</td>
<td>8.1 a</td>
<td>7.7 a</td>
<td>8.4 c</td>
<td>11 c</td>
<td>13 a</td>
<td>13 a</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Trial 2</th>
<th>%O₂</th>
<th>Day 1</th>
<th>Day 4</th>
<th>Day 6</th>
<th>Day 11</th>
<th>Day 15</th>
<th>Day 18</th>
<th>Day 20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>5.5 a</td>
<td>6.2 a</td>
<td>6.9 a</td>
<td>9.1 a</td>
<td>4.5 b</td>
<td>1.3 b</td>
<td>1.4 b</td>
<td></td>
</tr>
<tr>
<td>0.5kGy</td>
<td>5.3 a</td>
<td>5.9 a</td>
<td>6.7 a</td>
<td>9.4 a</td>
<td>11 a</td>
<td>11 a</td>
<td>9 a</td>
<td></td>
</tr>
<tr>
<td>1.0kGy</td>
<td>5.4 a</td>
<td>6 a</td>
<td>6.3 a</td>
<td>8.9 a</td>
<td>10 a</td>
<td>11 a</td>
<td>9.6 a</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>%CO₂</th>
<th>Day 1</th>
<th>Day 4</th>
<th>Day 6</th>
<th>Day 11</th>
<th>Day 15</th>
<th>Day 18</th>
<th>Day 20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>8.2 b</td>
<td>6.8 b</td>
<td>6.1 c</td>
<td>4.8 a</td>
<td>8.3 a</td>
<td>11 a</td>
<td>10 a</td>
</tr>
<tr>
<td>0.5kGy</td>
<td>8.4 a</td>
<td>7 a</td>
<td>6.3 b</td>
<td>4.8 a</td>
<td>4.3 b</td>
<td>5.2 b</td>
<td>6.5 b</td>
</tr>
<tr>
<td>1.0kGy</td>
<td>8.5 a</td>
<td>7.2 a</td>
<td>6.5 a</td>
<td>5 a</td>
<td>4.3 b</td>
<td>4.6 b</td>
<td>5.7 b</td>
</tr>
</tbody>
</table>

There are many reasons why the model may slightly differ from the experimental results. First, the data collected for the model was from fresh-cut cantaloupe irradiated in Ziploc bags with ambient air and then transferred to jars of ambient air, whereas the experimental data is from fresh-cut cantaloupe irradiated and stored in a bag with 4% oxygen and 10% carbon dioxide.
Therefore, the closed system generated a unique set of gas concentrations starting with high oxygen and low carbon dioxide and progressing to low oxygen and high carbon dioxide. The modified atmosphere packages maintained a low oxygen and high carbon dioxide headspace that was not observed in the closed system. This must be taken into consideration when designing a package based on closed system experiments. As seen from the data above, a package can be designed to maintain gas concentrations within critical ranges from closed system data. Second, closed system data was from samples irradiated at 0.4 and 0.6 kGy, and irradiation of these packages was 0.5 kGy. A limitation of irradiation was exposed here. The exact dosage of electron beam irradiation is difficult to achieve. Many variables come into play when trying to treat a product with a low dose. All settings in an irradiation facility may be the same as the day before, but a different dose may occur when running a very similar experiment. Not only does the actual irradiation emitted change, but the product composition, temperature, thickness
and etc., affects the average dose received as well. The intended average dose for the cantaloupe irradiated in this experiment was 0.4 and 0.8 kGy, in order to compare predicted respiration rates from the closed system data with experimental. Fortunately, the average dose did not exceed 1.0 kGy, the legal limit allowed by the FDA for fresh produce.

![Graph showing gas concentration over days](image)

Figure 5.8. Trial 2 predicted and observed oxygen and carbon dioxide levels inside designed modified atmosphere package containing irradiated fresh-cut cantaloupe stored at 3 °C.

**Microbiology**

The TPC counts were significantly higher in the controls through Day 11 and remained the highest through the duration in Trial 1 (Table 5.2). The largest treatment difference was a 2 log reduction on Day 6 between the control and 1.0 kGy treatment. The greatest increase in a treatment over time was the control from Day 1 to Day 6 with a ~2.3 log jump. The results are similar to Chapter 3. The microbiology counts were not significantly different at Day 14 and 18, yet at Day 8, 11, 14 and 18, there were significant differences in %O₂. It may be assumed that the reduction in respiration rate is
not solely due to reduction in microorganisms. In a paper by Bai and others (2001), fresh-cut cantaloupe was stored in MAPs flushed with 4% O2 plus 10% CO2 at 5 °C. The total plate count started just above 3 logs CFU/g and increased to ~9 logs CFU/g in 12 days. The respiration rate remained steady for the duration of the study, suggesting no effect of microorganisms. There were no significant differences between treatments in yeast and mold counts at all storage dates tested (Table 5.2).

Table 5.2. Total plate count (TPC) and yeast and mold count (Y+M) of irradiated and non-irradiated fresh-cut cantaloupe stored at 3 °C in modified atmosphere packages (Trial 1). CFU/g = colony forming units per gram. Means within a column sharing the same letter are not significantly different (p<0.05).

<table>
<thead>
<tr>
<th>Trial 1</th>
<th>CFU/g</th>
<th>Day 1</th>
<th>Day 6</th>
<th>Day 11</th>
<th>Day 14</th>
<th>Day 18</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>8.40E+04</td>
<td>a</td>
<td>1.59E+07</td>
<td>a</td>
<td>1.21E+09</td>
<td>a</td>
</tr>
<tr>
<td>0.5 kGy</td>
<td>1.57E+04</td>
<td>b</td>
<td>1.67E+06</td>
<td>b</td>
<td>1.49E+08</td>
<td>b</td>
</tr>
<tr>
<td>1.0 kGy</td>
<td>1.18E+04</td>
<td>b</td>
<td>1.58E+05</td>
<td>b</td>
<td>5.52E+07</td>
<td>b</td>
</tr>
</tbody>
</table>

| TPC          |           |       |       |        |        |        |
| Control      | 4.53E+03  | a     | 9.13E+04 | a   | 2.11E+06 | a   | 1.35E+05 | a   | 4.90E+05 | a   |
| 0.5 kGy      | 6.30E+02  | a     | 4.80E+04 | a   | 1.58E+05 | a   | 2.88E+05 | a   | 6.50E+05 | a   |
| 1.0 kGy      | 1.37E+03  | a     | 3.75E+03 | a   | 1.48E+05 | a   | 1.98E+05 | a   | 5.05E+06 | a   |

In Trial 2, the TPC counts were ~1.5 logs lower than the counts from Trial 1 on Day 1 (Table 5.3). There were significant differences with the control being the highest at all storage dates. The largest increase in counts in the control was between Day 6 and Day 11, almost 3 logs. This increase did not take place in the 0.5 kGy sample until between Day 15 and 20 and between Day 11 and 15 for the 1.0 kGy. The %O2 increased and the %CO2 decreased between Day 6 and 11 in all samples. There seemed to be no relationship between respiration and microorganism count. There were no significant differences between treatments for yeast and mold counts at all storage dates.

Results were similar to those reported by Ahn and others (2005) for minimally processed salted Chinese cabbage treated with MAP and irradiation during refrigerated
storage. Total aerobic bacteria count reductions of 0.7 and 1.5 logs were observed at time 0 in packages flushed with 25% CO2 plus 75% N2 and irradiated at 0.5 kGy and 1.0 kGy, respectively. Initial populations of total aerobic bacteria in salted Chinese cabbage were significantly reduced by gamma irradiation at 0.5 and 1.0 kGy (p < 0.05).

Table 5.3. Total plate count (TPC) and yeast and mold count (Y+M) of irradiated and non-irradiated fresh-cut cantaloupe stored at 3 °C in modified atmosphere packages (Trial 2). CFU/g = colony forming units per gram. Means within a column sharing the same letter are not significantly different (p<0.05).

<table>
<thead>
<tr>
<th>Trial 2</th>
<th>CFU/g</th>
<th>Day 1</th>
<th>Day 6</th>
<th>Day 11</th>
<th>Day 15</th>
<th>Day 20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td></td>
<td>3.08E+03 a</td>
<td>2.20E+04 a</td>
<td>1.03E+07 a</td>
<td>9.31E+08 a</td>
<td>1.15E+09 a</td>
</tr>
<tr>
<td>TPC</td>
<td></td>
<td>7.50E+02 b</td>
<td>7.00E+02 b</td>
<td>1.58E+04 b</td>
<td>5.28E+04 b</td>
<td>1.63E+08 b</td>
</tr>
<tr>
<td>0.5 kGy</td>
<td></td>
<td>2.83E+02 c</td>
<td>2.30E+02 b</td>
<td>6.00E+03 b</td>
<td>3.23E+06 b</td>
<td>2.72E+08 b</td>
</tr>
<tr>
<td>Y+M</td>
<td></td>
<td>1.00E+01 a</td>
<td>1.00E+01 a</td>
<td>2.90E+03 a</td>
<td>7.90E+04 a</td>
<td>2.43E+05 a</td>
</tr>
<tr>
<td>0.5 kGy</td>
<td></td>
<td>1.00E+01 a</td>
<td>1.00E+01 a</td>
<td>1.03E+03 a</td>
<td>3.86E+04 a</td>
<td>5.83E+05 a</td>
</tr>
<tr>
<td>1.0 kGy</td>
<td></td>
<td>1.00E+01 a</td>
<td>1.00E+01 a</td>
<td>1.00E+02 a</td>
<td>1.35E+04 a</td>
<td>4.49E+05 a</td>
</tr>
</tbody>
</table>

The quality of fresh-cut cantaloupe cubes in a study by Bai and others (2001) remained acceptable even though bacterial counts increased above 8 logs CFU/g. Yeast and mold were also less numerous in these trial as with others fresh-cut produce studies (Nguyen-The and Cartin, 1994). Two benefits of elevated carbon dioxide are its fungistatic and bacteristatic characteristics against many spoilage organisms that are able to multiply at refrigerator temperatures, and the ability to prolong the lag phase of spoilage organisms (Enfors and Molin, 1978).

**Texture**

The significant differences observed in the texture of the fresh-cut cantaloupe in Trial 1 were likely the result of variation from piece to piece rather than effect of treatment or storage (Table 5.4). Considerable variability from melon to melon was noted while processing. The melons in Trial 2 were much more consistent in texture.
significant differences between treatments were observed at any storage dates. The texture readings in Trial 2 remained steady across time with no interaction effect between treatment and storage. No consistent differences in texture were reported in Chinese cabbage irradiated at 0.5 or 1.0 kGy and stored in MAP at 4 °C (Ahn and others, 2005).

Table 5.4. Texture (kg) of irradiated and non-irradiated fresh-cut cantaloupe during storage at 3 °C in modified atmosphere packages. Means within a column sharing the same letter are not significantly different (p<0.05).

<table>
<thead>
<tr>
<th>Trial 1</th>
<th>max kg</th>
<th>Day 1</th>
<th>Day 6</th>
<th>Day 11</th>
<th>Day 14</th>
<th>Day 18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>1.214 a</td>
<td>0.919 a</td>
<td>0.863 b</td>
<td>1.16 a</td>
<td>0.891 a</td>
<td></td>
</tr>
<tr>
<td>0.5kGy</td>
<td>0.903 b</td>
<td>0.688 a</td>
<td>1.199 a</td>
<td>0.793 b</td>
<td>1.012 a</td>
<td></td>
</tr>
<tr>
<td>1.0kGy</td>
<td>0.93 b</td>
<td>0.824 a</td>
<td>1.068 ab</td>
<td>1.092 a</td>
<td>0.869 a</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Trial 2</th>
<th>max kg</th>
<th>Day 1</th>
<th>Day 6</th>
<th>Day 11</th>
<th>Day 15</th>
<th>Day 20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>1.116 a</td>
<td>1.069 a</td>
<td>0.997 a</td>
<td>1.078 a</td>
<td>1.08 a</td>
<td></td>
</tr>
<tr>
<td>0.5kGy</td>
<td>1.167 a</td>
<td>1.216 a</td>
<td>1.033 a</td>
<td>1.024 a</td>
<td>1.136 a</td>
<td></td>
</tr>
<tr>
<td>1.0kGy</td>
<td>1.056 a</td>
<td>1.068 a</td>
<td>0.989 a</td>
<td>1.073 a</td>
<td>1.084 a</td>
<td></td>
</tr>
</tbody>
</table>

Color

The L*, a* and b* values observed over time are listed in Table 5.5. In Trial 1, there were significant differences in L* values only at Day 1. The a* and b* values did not differ significantly throughout the duration of the storage. The differences in color were attributed more to piece to piece variation than effect of treatment. No specific trends were seen across time within treatments (Table 5.6). The color of fresh-cut cantaloupe irradiated or not remained stable for 18 days. These results are very similar to those found by Lamikanra and others (2000), where no significant changes occurred in lightness (L*), hue and chroma of fresh-cut cantaloupe stored at 4 °C for 7 days. In contrast, in another study (Lamikanra and Watson, 2000), storage of fresh-cut cantaloupe at 4 °C for 25 days resulted in considerable changes in hue, chroma and L* values. Lamikanra and Watson (2000) observed bleaching of cantaloupe, which was attributed to
oxidation of $B$-carotene. This may not have been a problem in this research due to the
low oxygen atmosphere maintained by the MAP.

Table 5.5. Color (L*, a*, b*) of irradiated and non-irradiated fresh-cut cantaloupe during
storage at 3 °C in modified atmosphere packages, by treatment (Trial 1).
Means within a column sharing the same letter are not significantly different
(p<0.05).

<table>
<thead>
<tr>
<th></th>
<th>Day 1</th>
<th>Day 6</th>
<th>Day 11</th>
<th>Day 14</th>
<th>Day 18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>68.76 a</td>
<td>59.33 a</td>
<td>61.94 a</td>
<td>65.56 a</td>
<td>64.98 a</td>
</tr>
<tr>
<td>0.5kGy</td>
<td>64.38 ab</td>
<td>59.23 a</td>
<td>66.41 a</td>
<td>65.38 a</td>
<td>63.75 a</td>
</tr>
<tr>
<td>1.0kGy</td>
<td>62.49 b</td>
<td>58.99 a</td>
<td>63.38 a</td>
<td>63.89 a</td>
<td>61.82 a</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Day 1</th>
<th>Day 6</th>
<th>Day 11</th>
<th>Day 14</th>
<th>Day 18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>11.59 a</td>
<td>11.74 a</td>
<td>12.08 a</td>
<td>11.77 a</td>
<td>12.69 a</td>
</tr>
<tr>
<td>0.5kGy</td>
<td>11.93 a</td>
<td>11.46 a</td>
<td>12.48 a</td>
<td>12.35 a</td>
<td>12.49 a</td>
</tr>
<tr>
<td>1.0kGy</td>
<td>12.01 a</td>
<td>11.62 a</td>
<td>12.12 a</td>
<td>12.56 a</td>
<td>12.69 a</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Day 1</th>
<th>Day 6</th>
<th>Day 11</th>
<th>Day 14</th>
<th>Day 18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>33.16 a</td>
<td>31.09 a</td>
<td>31.03 a</td>
<td>31.58 a</td>
<td>32.06 a</td>
</tr>
<tr>
<td>0.5kGy</td>
<td>31.73 a</td>
<td>29.52 a</td>
<td>32.41 a</td>
<td>33.35 a</td>
<td>31.45 a</td>
</tr>
<tr>
<td>1.0kGy</td>
<td>31.40 a</td>
<td>30.28 a</td>
<td>32.63 a</td>
<td>32.64 a</td>
<td>31.18 a</td>
</tr>
</tbody>
</table>

In Trial 2, significant differences between treatments in L* values were observed
on Day 6 (Table 5.7). The a* values differed significantly only on Day 20. The b*
values differed significantly on Day 6 and 20. As in Trial 1, no trends were observed
with respect to the effect of treatment. An effect of storage was seen in Trial 2, with the
control and 1.0 kGy samples having the significantly lowest L*, a* and b* values on Day
20. The 0.5 kGy samples remained very stable over time.

**Sensory**

**Trial 1**

The trained panelists rated the appearance attribute orange, of the control
significantly lower than that of the irradiated samples when averaged across all storage
times (Table 5.8). Orange was significantly different between Day 1 and Day 18 within
Table 5.6. Color (L*, a*, b*) of irradiated and non-irradiated fresh-cut cantaloupe during storage at 3 °C in modified atmosphere packages, by storage. Means within a column sharing the same letter are not significantly different (p<0.05).

<table>
<thead>
<tr>
<th>Trial</th>
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<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L</td>
<td>a</td>
</tr>
<tr>
<td>Day 1</td>
<td>68.76 a</td>
<td>11.59 b</td>
</tr>
<tr>
<td>Day 6</td>
<td>59.33 c</td>
<td>11.74 b</td>
</tr>
<tr>
<td>Day 11</td>
<td>61.94 c</td>
<td>12.08 ab</td>
</tr>
<tr>
<td>Day 14</td>
<td>65.56 b</td>
<td>11.77 b</td>
</tr>
<tr>
<td>Day 18</td>
<td>64.98 b</td>
<td>12.69 a</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>0.5kGy</th>
<th>0.5kGy</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>a</td>
</tr>
<tr>
<td>Day 1</td>
<td>64.38 a</td>
</tr>
<tr>
<td>Day 6</td>
<td>59.23 b</td>
</tr>
<tr>
<td>Day 11</td>
<td>66.41 a</td>
</tr>
<tr>
<td>Day 14</td>
<td>65.38 a</td>
</tr>
<tr>
<td>Day 18</td>
<td>63.75 a</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1.0kGy</th>
<th>1.0kGy</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>a</td>
</tr>
<tr>
<td>Day 1</td>
<td>62.49 ab</td>
</tr>
<tr>
<td>Day 6</td>
<td>58.99 b</td>
</tr>
<tr>
<td>Day 11</td>
<td>63.38 a</td>
</tr>
<tr>
<td>Day 14</td>
<td>63.89 a</td>
</tr>
<tr>
<td>Day 18</td>
<td>61.82 ab</td>
</tr>
</tbody>
</table>

Table 5.7. Color (L*, a*, b*) of irradiated and non-irradiated fresh-cut cantaloupe during storage at 3 °C in modified atmosphere packages, by treatment (Trial 2). Means within a column sharing the same letter are not significantly different (p<0.05).

<table>
<thead>
<tr>
<th></th>
<th>Day 1</th>
<th>Day 6</th>
<th>Day 11</th>
<th>Day 15</th>
<th>Day 20</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>66.54 a</td>
<td>68.23 a</td>
<td>68.63 a</td>
<td>66.90 a</td>
<td>63.53 a</td>
</tr>
<tr>
<td>0.5kGy</td>
<td>65.93 a</td>
<td>64.66 b</td>
<td>65.98 a</td>
<td>65.23 a</td>
<td>66.40 a</td>
</tr>
<tr>
<td>1.0kGy</td>
<td>68.77 a</td>
<td>65.68 ab</td>
<td>64.08 a</td>
<td>64.78 a</td>
<td>61.97 a</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Day 1</th>
<th>Day 6</th>
<th>Day 11</th>
<th>Day 15</th>
<th>Day 20</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>11.13 a</td>
<td>11.36 a</td>
<td>10.61 a</td>
<td>10.88 a</td>
<td>9.99 ab</td>
</tr>
<tr>
<td>0.5kGy</td>
<td>11.31 a</td>
<td>11.33 a</td>
<td>10.99 a</td>
<td>10.93 a</td>
<td>11.03 a</td>
</tr>
<tr>
<td>1.0kGy</td>
<td>10.40 a</td>
<td>10.54 a</td>
<td>10.83 a</td>
<td>11.53 a</td>
<td>9.64 b</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Day 1</th>
<th>Day 6</th>
<th>Day 11</th>
<th>Day 15</th>
<th>Day 20</th>
</tr>
</thead>
<tbody>
<tr>
<td>b</td>
<td>30.97 a</td>
<td>31.73 a</td>
<td>31.11 a</td>
<td>30.60 a</td>
<td>27.63 ab</td>
</tr>
<tr>
<td>0.5kGy</td>
<td>30.40 a</td>
<td>29.68 b</td>
<td>30.58 a</td>
<td>29.28 a</td>
<td>31.03 a</td>
</tr>
<tr>
<td>1.0kGy</td>
<td>30.27 a</td>
<td>30.55 ab</td>
<td>30.08 a</td>
<td>30.68 a</td>
<td>26.45 b</td>
</tr>
</tbody>
</table>
all treatments with a slight increase over time. Day 6 is the only day that colorimeter readings for a* and b* were both higher in the control. The other appearance attribute, moist was rated lowest in the control over all storage times. Within all treatments, moist, increased over time and was rated significantly different only between Day 14 and Day 18. There was no storage*treatment interaction for the appearance attributes.

The texture attribute firmness was rated significantly higher in the control than both irradiated samples. There was no storage*treatment interaction effect or trend in firmness over time with the only difference between Day 1 and Day 11. Crispness was rated the lowest in the 1.0 kGy sample. Firmness and crispness being significantly lower in the 1.0 kGy treatment is consistent with the literature where higher doses of irradiation are more likely to induce softening of tissue (Massey and Bourke, 1967; Kertesz and others 1964; Gunes and others, 2001b). As previously stated, considerable variability from melon to melon in texture was noted while processing. No differences between treatments were observed in mealy over all time, nor did it change during storage. Juicy was significantly highest in the 1.0 kGy treatment, but no differences were observed during storage with no interaction effect. A storage*treatment interaction effect was observed in crispness and mealy, although no clear trends were observed by treatment over time.

The sweetness attribute was rated significantly lowest in the control compared to both irradiated samples. A significant decrease in sweetness was observed on Day 18. No storage*treatment interaction effect was observed in sweetness. Differences in sweetness may be attributed to lower consumption rates of carbohydrates (glucose, fructose and sucrose) due to lower respiration rates in irradiated tissue. Similar results
Table 5.8. Sensory results (Trial 1), by treatment and over storage of irradiated and non-irradiated fresh-cut cantaloupe (0 to 15 scale), stored at 3 °C. CFI* = Cantaloupe Flavor Intensity. Means within a column sharing the same letter are not significantly different (p<0.05). ns = non significant, * = significant (p<0.05)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Orange</th>
<th>Moist</th>
<th>Firmness</th>
<th>Mealy</th>
<th>Juicy</th>
<th>Crispness</th>
<th>Sweetness</th>
<th>CFI*</th>
<th>Off Flavor</th>
<th>Pumpkin</th>
<th>Accept.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>7.09 b</td>
<td>7.59 b</td>
<td>8 a</td>
<td>0.84 a</td>
<td>7.31 b</td>
<td>8.06 a</td>
<td>6.53 b</td>
<td>6.8 b</td>
<td>2.65 a</td>
<td>0.67 a</td>
<td>6.61 b</td>
</tr>
<tr>
<td>0.5 kGy</td>
<td>7.73 a</td>
<td>8.1 a</td>
<td>7.47 b</td>
<td>0.82 a</td>
<td>7.73 ab</td>
<td>8.02 a</td>
<td>7.01 a</td>
<td>7.75 a</td>
<td>1.8 b</td>
<td>0.43 a</td>
<td>7.37 a</td>
</tr>
<tr>
<td>1.0 kGy</td>
<td>7.63 a</td>
<td>8.13 a</td>
<td>7.15 b</td>
<td>0.71 a</td>
<td>8.02 a</td>
<td>7.03 b</td>
<td>7.21 a</td>
<td>8.01 a</td>
<td>1.72 b</td>
<td>0.43 a</td>
<td>7.53 a</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Storage</th>
<th>Orange</th>
<th>Moist</th>
<th>Firmness</th>
<th>Mealy</th>
<th>Juicy</th>
<th>Crispness</th>
<th>Sweetness</th>
<th>CFI*</th>
<th>Off Flavor</th>
<th>Pumpkin</th>
<th>Accept.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 1</td>
<td>7.24 b</td>
<td>7.61 b</td>
<td>7.87 a</td>
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<td>8.06 a</td>
<td>6.87 a</td>
<td>7.75 ab</td>
<td>1.41 bc</td>
<td>0.68 a</td>
<td>7.88 a</td>
</tr>
<tr>
<td>Day 6</td>
<td>7.4 a</td>
<td>7.61 b</td>
<td>7.68 ab</td>
<td>0.51 a</td>
<td>7.63 a</td>
<td>8.15 a</td>
<td>7.44 a</td>
<td>8.49 a</td>
<td>0.71 c</td>
<td>0.38 a</td>
<td>8.63 a</td>
</tr>
<tr>
<td>Day 11</td>
<td>7.55 ab</td>
<td>7.95 b</td>
<td>7.17 b</td>
<td>0.59 a</td>
<td>7.63 a</td>
<td>7.31 b</td>
<td>7.01 a</td>
<td>7.52 ab</td>
<td>1.38 bc</td>
<td>0.29 a</td>
<td>7.45 ab</td>
</tr>
<tr>
<td>Day 14</td>
<td>7.57 ab</td>
<td>8.22 ab</td>
<td>7.43 ab</td>
<td>0.69 a</td>
<td>7.69 a</td>
<td>7.21 b</td>
<td>7 a</td>
<td>7.35 b</td>
<td>2.61 b</td>
<td>0.51 a</td>
<td>6.21 b</td>
</tr>
<tr>
<td>Day 18</td>
<td>7.86 a</td>
<td>8.71 a</td>
<td>7.46 ab</td>
<td>1.57 a</td>
<td>8.05 a</td>
<td>7.69 ab</td>
<td>5.72 b</td>
<td>5.53 c</td>
<td>6.03 a</td>
<td>0.75 a</td>
<td>4.2 c</td>
</tr>
</tbody>
</table>

Interact ns ns ns * ns * ns ns * ns * ns *
Table 5.9. Sensory results (Trial 2), by treatment and over storage of irradiated and non-irradiated fresh-cut cantaloupe (0 to 15 scale), stored at 3 °C. CFI* = Cantaloupe Flavor Intensity. Means within a column sharing the same letter are not significantly different (p<0.05). ns = non significant, * = significant (p<0.05)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Orange</th>
<th>Moist</th>
<th>Firmness</th>
<th>Mealy</th>
<th>Juicy</th>
<th>Crispness</th>
<th>Sweetness</th>
<th>CFI*</th>
<th>Off Flavor</th>
<th>Pumpkin</th>
<th>Accept.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>6.84 a</td>
<td>7.32 a</td>
<td>7.93 a</td>
<td>0.49 a</td>
<td>6.93 ab</td>
<td>7.96 a</td>
<td>6.45 a</td>
<td>7.34 a</td>
<td>1.76 a</td>
<td>0.26 a</td>
<td>7.2 b</td>
</tr>
<tr>
<td>0.5 kGy</td>
<td>6.45 b</td>
<td>6.98 b</td>
<td>7.98 a</td>
<td>0.41 a</td>
<td>6.77 b</td>
<td>8.02 a</td>
<td>6.48 a</td>
<td>7.4 a</td>
<td>1.01 b</td>
<td>0.32 a</td>
<td>7.57 ab</td>
</tr>
<tr>
<td>1.0 kGy</td>
<td>6.7 a</td>
<td>7.23 ab</td>
<td>7.68 a</td>
<td>0.44 a</td>
<td>7.21 a</td>
<td>7.71 a</td>
<td>6.71 a</td>
<td>7.63 a</td>
<td>0.91 b</td>
<td>0.23 a</td>
<td>7.89 a</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Storage</th>
<th>Orange</th>
<th>Moist</th>
<th>Firmness</th>
<th>Mealy</th>
<th>Juicy</th>
<th>Crispness</th>
<th>Sweetness</th>
<th>CFI*</th>
<th>Off Flavor</th>
<th>Pumpkin</th>
<th>Accept.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 1</td>
<td>7.02 a</td>
<td>7.36 a</td>
<td>7.78 ab</td>
<td>0.32 b</td>
<td>7.09 a</td>
<td>7.71 ab</td>
<td>6.9 a</td>
<td>8.41 a</td>
<td>0.95 b</td>
<td>0.33 a</td>
<td>7.88 ab</td>
</tr>
<tr>
<td>Day 6</td>
<td>6.39 a</td>
<td>7.22 a</td>
<td>8.38 a</td>
<td>0.33 b</td>
<td>6.77 a</td>
<td>8.47 a</td>
<td>6.38 a</td>
<td>7.59 a</td>
<td>0.69 b</td>
<td>0.25 a</td>
<td>7.83 ab</td>
</tr>
<tr>
<td>Day 11</td>
<td>6.74 a</td>
<td>7.35 a</td>
<td>8.07 ab</td>
<td>0.65 a</td>
<td>7.39 a</td>
<td>7.93 ab</td>
<td>6.45 a</td>
<td>7.64 ab</td>
<td>0.95 b</td>
<td>0.26 a</td>
<td>8.22 a</td>
</tr>
<tr>
<td>Day 15</td>
<td>6.58 a</td>
<td>6.97 a</td>
<td>7.55 ab</td>
<td>0.35 b</td>
<td>6.87 a</td>
<td>7.5 b</td>
<td>6.18 a</td>
<td>6.54 b</td>
<td>0.94 b</td>
<td>0.25 a</td>
<td>7.13 bc</td>
</tr>
<tr>
<td>Day 20</td>
<td>6.62 a</td>
<td>6.96 a</td>
<td>7.44 b</td>
<td>0.6 a</td>
<td>6.73 a</td>
<td>7.82 ab</td>
<td>6.87 a</td>
<td>7.05 b</td>
<td>2.82 a</td>
<td>0.26 a</td>
<td>6.59 c</td>
</tr>
</tbody>
</table>

Interact  * ns ns ns * ns * * * ns *
were found with fresh-cut irradiated carrots compared to non irradiated, whereby controls consumed twice the amount of overall carbohydrates within 96 hours at 20 °C (Chervin and others, 1992).

Cantaloupe flavor intensity (CFI) was rated significantly lower in the control compared to both irradiated samples. Within all treatments, a decline over time was observed with significant differences on both Day 14 and 18. No storage*treatment interaction effect was observed in cantaloupe flavor intensity.

Off flavor was rated significantly highest in the control compared to both irradiated samples. Within all treatments, an increase over time was observed with significant differences on Days 6, 14 and 18. A storage*treatment interaction effect was observed in off flavor such that the off flavor was significantly lower on Day 14 in both irradiated samples that in the control (Figure 5.9). An increase in off flavor of the control was seen from Day 6 through Day 11. Not only did irradiation not impart any off flavors, it delayed off flavor formation. In both irradiated samples off flavor only significantly increased on Day 18.

No differences were observed in the pumpkin attribute.

The control was rated significantly the least acceptable between treatments. Acceptability declined significantly for all treatments during storage with a storage*treatment interaction effect such that the acceptability of the control was significantly lower on Day 11 and Day 14 for both irradiated samples (Figure 5.10).

Fresh-cut produce generally loses freshness, flavor and salability while stored in refrigerated conditions due to physiological and biochemical changes (Watada and Qi, 1999). The control decreased in sweetness, cantaloupe flavor intensity and increased in
off flavor more rapidly than the irradiated samples. The sustained higher microbiological counts and increase in respiration rate of the controls may be the main causes for

Figure 5.9. Off flavor rating of treatments at each storage (3 °C). Means sharing the same letter within a storage time are not significantly different (p<0.05).

Figure 5.10. Acceptability rating of treatments at each storage date (3 °C). Means sharing the same letter within a storage time are not significantly different (p<0.05).
these sensory differences. *Lactobacilli* spp. are most likely the microorganism responsible (Salama and others, 1995). *Lactobacilli* spp. ferment glucose, fructose and sucrose during growth while producing lactic acid. Fruit flavor deterioration may be due to increased lipase production by lactic acid bacteria (Lamikanra and others, 2000; Chandler and Ranganathon, 1975; Meyers and others, 1996). The higher respiration rate leads to increased respiratory metabolism and senescence.

**Trial 2**

The 0.5 kGy sample was slightly lower in the orange attribute compared to the other treatments. No effect of storage was seen in orange color, but there was a storage*treatment interaction effect (Table 5.9) that resulted in the control and 0.5 kGy samples being rated significantly lower on Day 20 than on all other days, while the 1.0 kGy sample was rated significantly higher than all other days of all treatments. This large difference may be from the panelists reaction to seeing a clear difference for the first time and overrating the 1.0 kGy sample. No apparent differences explain the interaction effect. The moist attribute did not decrease during storage in Trial 2, with slight differences in treatment and no storage*treatment interaction effect.

No differences in firmness due to treatment were observed. Within all treatments, a decline over time was observed with a significant difference between Day 6 and Day 20. No storage*treatment interaction effect was observed in firmness. No differences in crispness due to treatment were observed, and there were no clear trends during storage. The fruit used in Trial 2 were more consistent with regards to texture at time 0 and remained stable over the duration of the storage.
No differences in mealy due to treatment were observed, and increased only slightly on Day 11 and Day 20. No storage*treatment interaction effect was observed for mealy.

Juicy was the only texture attribute with significant differences in treatments over all storage times, with the 0.5 kGy sample the lowest and the 1.0 kGy the highest. No effect of storage was seen but there was a storage*treatment interaction effect. This interaction showed no consistent trends in the juicy attribute.

There were no differences in sweetness due to treatment or storage. However, a storage*treatment interaction effect was observed for sweetness. Sweetness was determined to be significantly highest in the 1.0 kGy sample on both Day 11 and Day 20 (Figure 5.11). Differences in sweetness may be attributed to lower consumption rates of carbohydrates (glucose, fructose and sucrose) due to lower respiration rates in irradiated tissue as observed in Trial 1 and others (Chervin and others, 1992).

![Figure 5.11. Sweetness rating of treatments at each storage (3 °C). Means sharing the same letter within a storage time are not significantly different (p<0.05).](image)
No differences in cantaloupe flavor intensity (CFI) between treatments were observed when averaged across all storage times, but there were significant differences during storage over all treatments with a storage*treatment interaction effect. The 1.0 kGy treatment had higher CFI on Day 20 (Figure 5.12).

![Figure 5.12. Cantaloupe flavor intensity (CFI) rating of treatments at each storage date (3 °C). Means sharing the same letter within a storage time are not significantly different (p<0.05).](image)

A significant interaction between treatment and storage was also found for off flavor (Figure 5.13). On Day 15 and 20, the control was significantly the highest in off flavor. At Day 20, the 0.5 kGy treatment also had a higher off flavor rating than the 1.0 kGy treatment.

No notable differences in the pumpkin attribute were observed.

The 1.0 kGy sample was rated significantly higher in acceptability than the control when averaged across all storage times (Table 5.9). Acceptability tended to decrease during storage and there was a storage*treatment interaction. The interaction shows that
there were significant differences in acceptability only on Day 20, when the control had
the lowest acceptability and the 1.0 kGy treatment the highest (Figure 5.14).

Figure 5.13. Off flavor rating of treatments at each storage date (3 °C). Means sharing
the same letter within a storage time are not significantly different (p<0.05).

Figure 5.14. Acceptability rating of treatments at each storage date (3 °C). Means
sharing the same letter within a storage time are not significantly different (p<0.05).
Conclusion

With known prediction equations for respiration rate of fresh-cut cantaloupe and gas transmission rate properties of packaging films, an optimal MAP was designed. Total plate count was significantly reduced in irradiated samples through Day 11 in Trial 1 and through Day 20 in Trial 2. No trends in color or texture were observed with respect to the effect of treatment in either Trial. Irradiated samples had a lower and more stable rate of respiration over the duration of the study than non-irradiated samples. Sensory evaluation rated the 1.0 kGy sample highest in sweetness and cantaloupe flavor intensity and lowest in off flavor after 14 days of storage in Trial 1 and after 20 days of storage in Trial 2. Low dose electron beam irradiation of fresh-cut cantaloupe with MAP offers promise as a method of extending shelf-life.
CHAPTER 6
CONCLUSIONS

Low dose electron beam irradiation of fresh-cut cantaloupe stored in modified atmosphere packages (MAP) offers promise as a method of increasing quality and shelf life. Knowledge of the effects of irradiation on product respiration rates, as summarized in Eqn. (3.1) or in other forms such as polynomial or Michaelis-Menten fits, should provide a means to develop MAP that could further enhance the ability of irradiation to extend fresh-cut cantaloupe shelf-life.

The Michaelis-Menten enzyme kinetics equation may not be a suitable model for all fresh-cut produce, especially those with low respiration rates. A polynomial model fit the oxygen consumption and carbon dioxide evolution data for fresh-cut cantaloupe very well and most importantly in the critical ranges for MAP. An Arrhenius equation can be used to express the oxygen and carbon dioxide transmission rates of packaging polymers over a range of temperatures. Determination of prediction equations for respiration rate of produce over a range of oxygen and carbon dioxide concentrations and transmission rates of packaging films allows for an optimal MAP to be easily designed.

With known prediction equations for respiration rate of fresh-cut cantaloupe and transmission rates of packaging films, an optimal MAP was designed. Internal gas composition of packages were determined similar to predictions. Total plate count was significantly reduced in irradiated samples through Day 11 in Trial 1 and through Day 20 in Trial 2. No trends in color or texture were observed with respect to the effect of treatment in either trial. Irradiated samples had a lower and more stable rate of
respiration over the duration of the study than non-irradiated samples. Sensory
evaluation rated the 1.0 kGy sample highest in sweetness and cantaloupe flavor intensity
and lowest in off flavor after 14 days of storage in Trial 1 and after 20 days of storage in
Trial 2. Low dose electron beam irradiation of fresh-cut cantaloupe with MAP offers
promise as a method of extending shelf-life. The suppression of respiration rate rise,
decrease of microbial load, extension of shelf-life with no adverse effects on sensory
characteristics, and the ability to treat in the final package make irradiation an excellent
tool for the fresh-cut cantaloupe market.
REFERENCES


Watkins CB. 2000. Responses of horticultural commodities to high carbon dioxide as related to modified atmosphere packaging; limits to the expanded use of MAP. HortTech 10:501-506.


BIOGRAPHICAL SKETCH

I was born and raised in West Palm Beach, Florida. I obtained my undergraduate degree in food science and human nutrition with a business minor. I then completed my master’s in food science working with mango and carambola treated with high pressure processing. During my pursuit of a doctoral degree in food science, I obtained a master’s in decision information science. All degrees were completed at the University of Florida in Gainesville, Florida.