CALIFORNIA ENERGY COMMISSION

Energy Research and Development Division

**FINAL PROJECT REPORT**

# Commercial Demonstration of Innovative, Energy-Efficient Infrared Processing of Healthy Fruit and Vegetable Snacks

**Gavin Newsom, Governor**

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# PREFACE

The California Energy Commission's Energy Research and Development Division manages the Natural Gas Research and Development program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmissionand distribution and transportation.

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- Energy-Related Environmental Research
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# ABSTRACT

An innovative and energy efficient commercial scale sequential infrared dry-blanching and hot air drying system was demonstrated to show how to produce healthy fruit and vegetable snacks. The demonstration system was successfully designed, built and tested by the United States Department of Agriculture, University of California, Davis and the Treasure8 food processing plant in Richmond (Contra Costa County), California. In drying tests, the system was able to process between 173 and 292 pounds per hour of fresh thin apple, carrot, kale, pear, sweet potato, pepper and zucchini slices, reducing moisture content to about 5 percent.

The chips dried using this technology kept the attractive color, and taste, retained most of the nutrients, were crispier and crunchier, and maintained the same level of overall acceptance compared to freeze-dried products. The energy savings by this drying technology ranged from 26 percent to almost 73 percent compared to traditional oil frying and when compared to freeze drying, energy savings ranged from 62 percent to more than 82 percent. Additionally, the project achieved significant fresh water savings from the elimination of the blanching process normally used to produce this type of snack food.

**Keywords**: infrared, dry-blanching, hot-air drying, fruit and vegetables, snacks, energy-saving

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# TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

Page

# EXECUTIVE SUMMARY

## Introduction

Food processing is a $50 billion industry and the third largest industrial energy user in California. The annual energy consumption in this industry is around 590 million therms of natural gas and 3.7 billion kilowatt-hours (kWh) of electricity. A challenge for the food industry is to ensure adequate electricity and gas supplies while reducing greenhouse gas emissions. The California Energy Commission's *Energy Efficiency Roadmap for the California Food Processing and Beverage Industry* identifies improving energy and water efficiency as a research priority*.*

Snacks are a $31 billion industry in the United States and the demand for healthy snacks with fewer calories and lower fat content is increasing. The most common method of producing fruit and vegetable-based snacks uses freeze-drying. The use of freeze-drying in food industry, however, is an energy-intensive technology with high capital costs due to the type of equipment required. Hot-air drying is another widely used drying method but, when used alone, cannot produce crispy snacks with flavor, color, and texture that consumers desire. Hot-air drying is also energy-intensive because the product needs prolonged drying time in ovens. In normal production, fruit and vegetable snacks are usually blanched using hot water, steam, or both to inactivate enzymes to prevent color deterioration and extend the shelf life of the products. The blanching method causes high nutrient loss, requires large amounts of fresh water, and generates significant wastewater that must be treated before discharge.

## Project Purpose and Process

This project demonstrated a novel, cost-effective, and energy-efficient "sequential infrared dry-blanching/dehydration and hot air drying" technology to produce healthy and crispy vegetable and fruit snacks with desirable texture, color, and flavor. The technology uses infrared radiation for heating to achieve simultaneous dry blanching and partial dehydration of fresh vegetables and fruits, followed by final drying using hot air. Infrared radiation is emitted in the form of electromagnetic waves or electromagnetic radiation and usually affects the surface of a material before penetrating to the inside. Because the radiation can be transferred from the heating element to the product surface without heating the surrounding air, it is highly efficient.

In this project, the team:

- Developed and designed a commercial production plant with sequential infrared dry-blanching/dehydration and hot air drying technology.
- Optimized processing and operation to manufacture high-quality products by quantifying the product quality and energy consumption.

- Disseminated technology benefits to snack food processors and related organizations so they can achieve energy savings and make these healthy snack products available in the global marketplace.

The team documented the benefits and viability of the new technology on a commercial scale for energy savings and reducing environmental pollution while producing new, healthy snacks with desirable texture, color, and flavor at reduced production costs.

## Project Results

The team demonstrated the commercial-scale system with a drying capacity of 75-100 kilograms (kg) (about 165-220 pounds) of fresh produce per hour. Drying tests were conducted using thin slices of apple, carrot, kale, pear, sweet potato, pepper, and zucchini with an average thickness of 1.27 to 3.39 millimeter (mm) (between 0.05 inch and 0.13 inch) and moisture content of about 79 percent to 95 percent. The infrared drying/dry-blanching followed by hot-air drying reduced the moisture content about 5 percent.

The drying tests showed the system could dry 78.5 kg/hour to 132.3 kg/hour (173-292 pounds/hour) of fresh fruit and vegetable slices into high-quality crispy and healthy chips with attractive color and taste while retaining most of the nutrients. The infrared dry-blanching inactivated 50 percent to 99 percent of the enzyme that causes browning of the product. Crispness tests with a textural analyzer confirmed that the chips produced by the technology were as crispy as those produced by traditional oil frying or freeze drying. The energy savings from the technology ranged from 26 percent to 72 percent compared to oil frying. Compared to freeze drying, the product savings ranged from 62 percent to 82 percent of the energy to produce chips with similar quality.

## Project Benefits

The team successfully demonstrated the feasibility of the sequential infrared dry-blanching/dehydration and hot-air-drying technology through a commercial-scale system using dry-blanching of fruits and vegetables to produce high-quality, crispy, healthy chips with attractive color and taste while retaining most of the healthy nutrients. The water use for blanching is completely eliminated, and the energy efficiency is improved three to four times compared to frying and freeze drying with a significant energy saving. The quality of the resulting dried chips is superior to that of fried chips without using oil and is on par with the quality of freeze-dried products.

California food processors blanch an estimated 453,000 tons of fresh fruits and vegetables annually. About 100-500 gallons of water are required to blanch 1 ton of fruit or vegetable. Because the dry-blanching technology of this project eliminates water blanching, it could save about 45 million to 225 million gallons of water. If 20 percent of the snack processors in California replace their current technologies with the sequential infrared dry-blanching/dehydration and hot-air-drying system, within five years the savings are estimated at 10 million to 40 million gallons of water, several million therms of natural gas due to elimination of hot water blanching and heating oil for deep frying, and savings in electricity due to elimination of freeze drying. The new technology will use catalytic infrared emitters powered by natural gas to dry blanch and dehydrate, which do not emit oxides of nitrogen, meaning that it is an environmentally friendly technology. These project results will serve as a model for a new blanching and drying technology with reduced energy consumption. The technology has been patented by the United States Department of Agriculture and exclusively licensed by Treasure8.

# CHAPTER 1: Introduction and Objectives

## Introduction

Food processing is the third largest industrial energy user in California, consuming more than 590 million therms of natural gas and more than 3,700 million kilowatt hours (kWh) of electricity while generating more than $50 billion annually to the state's economy. Using electricity, natural gas and other fuels represents 10 to 20 percent of operational cossectionts for food processing; the embedded energy in water and the costs of water treatment and disposal can add an additional 8 to 10 percent in variable costs. Meeting air emission standards or paying penalties may add another 2 to 5 percent to production costs. Improving energy and water efficiency has beenidentified as a research priority in the *Energy Efficiency Roadmap for the California Food Processing and Beverage Industry* (California Energy Commission, 2003). Drying and blanching are the two most common methods for processing fruits and vegetables requiring significant amounts of energy. Besides inefficient energy use, current technology uses steam or hot water to blanch the fruits and vegetables. This requires using natural water resources and creates wastewater. It is essential to develop economically viable, sustainable alternative drying and blanching methods with highenergy efficiency and no water use.

Producing healthy food snacks is one of the largest food industries in the U.S. with annual revenue of $31 billion. The most common method of producing fruit and vegetable-based snacks uses freeze-drying. However, freeze-drying in food industry is limited because it is an energy intensive technology with a high capital cost. Hot air drying is another widely used drying method, but when used alone it cannot produce crispy snacks with desirable flavor, color and texture. It is also energy intensive because of prolonged drying time. Fruit and vegetable snacks normally require blanching using hot water or steam or both. Blanching inactivates enzyme, reduces microbial population, and stabilizes color. enzyme inactivation is the most important since the enzymes can cause significant quality deterioration of processed fruits and vegetables during storage. The enzyme inactivation is normally achieved by heating the fruits and vegetables to a desired temperature (70-100°Centigrade [C]) using hot water or steam and holding the product for a certain period of time. Food processors commonly use hot water and steam blanching methods because they are easy to operate and have low initial capital costs. However, hot water and steam blanching have significant drawbacks such as low energy efficiency, texture deterioration, and losses of soluble solids, nutrients, phytochemicals, or flavors or all of these. Moreover, these current blanching methods generate significant wastewater. Various alternatives, such as microwave blanching/drying and high hydrostatic pressure blanching have beenstudied but have not been commercially used because of the high capital costs or low throughput.

The research team developed an energy efficient and dry blanching technology using infrared (IR) heating that overcomes most of the drawbacks of conventional blanching processes (Pan and McHugh, 2004). The results of these studies demonstrated that IR drying and dry-blanching of various fruits and vegetables reduced energy use and eliminated water use, and the fruits and vegetables had improved quality compared to traditional blanching and drying methods. Simultaneously, an innovative and energy efficient sequential infrared (IR) dry-blanching/dehydration and hot air drying (SIRDBHAD) technology was developed for producing healthy, crispy vegetable and fruit snacks with desirable texture, color and flavor. The SIRDBHAD technology is an energy efficient alternative to current blanching and freeze-drying methods, producing vegetable and fruit based crispy snacks. A simultaneous IR dry blanching and dehydration approach for blanching and partially dehydrating fruits and vegetables results in high product quality (Pan and McHugh, 2004). These previous results showed that SIRDBHAD is also a highly energy efficient process for blanching and partially drying fruits and vegetables (Zhu et al., 2010). Combined IR and hot air drying dramatically reduces processing time and energy consumption. Moreover, better quality products are produced compared with hot air and IR alone (Kocabiyik, 2012).

IR radiation is energy as electromagnetic waves or electromagnetic radiation, and it can be used for thermal processing of foodstuffs. Radiation heat first impinges on the surface of the material and then penetrates the inside. It can be transferred from the heating element to the product surface without heating the surrounding air and is highly efficient (Jones, 1992). Radiation heat transfer can occur between two bodies separated by a medium colder than both bodies (Cengal, 1998). The wavelength of IR falls in the spectrum of 0.76 to 1,000 micrometers (μm) and can typically be categorized into near infrared (NIR) (0.76-2μm), medium infrared (MIR) (2-4 μm), and far infrared (FIR) (4-1,000 μm). For agricultural food product processing, high temperatures corresponding to NIR radiation could cause product discoloration and quality deterioration; therefore, temperature must be controlled if NIR is used. FIR is associated with low temperature and energy emission. If the temperature is too low, the energy emitted may not be enough to meet the energy requirements in food processing. Useful temperatures of IR emission may be in the range of 150-2200°C, which corresponds to the IR peak wavelengths of 7-1.2 μm. Absorptivity and penetration capability (transmissivity) of IR may vary with wavelengths of radiation and the physical and chemical characteristics of the food product being treated. Matching the peak power region of the radiation source with maximum radiation absorption points of the wet materials could be important in the selection of IR emitters for achieving rapid heating. IR radiation energy can be generated with various types of emitters such as catalytic emitters, electric emitters, carbon emitters, and ceramic emitters by converting fossil fuels (such as natural gas) or electric energy into radiation energy. The electric and gas-fired MIR and FIR emitters have similar efficiencies (Johannes and Thijssen, 1997).

During the past several years, through the strong support of the partners and funding agencies, such as the Energy Innovations Small Grants programs of the California Energy Commission (CEC), California Department of Food and Agriculture (CDFA), United States Department of Agriculture (USDA)-Agricultural Research Service (ARS), California League of Food Processors (CLFP), infrared equipment manufacturers, and University of California, (UC) Davis, the team has investigated and proven the technical feasibility of SIRDBHAD for producing healthy snacks from different fruits and vegetables. It was, therefore, necessary to develop and design a commercial scale SIRDBHAD unit for demonstrating the advantages of the novel method and further improving energy efficiency and product quality.

# Project Objectives

The main goal of this project was to commerciallydemonstrate the SIRDBHAD technology for to produce healthy, crispy snacks from vegetables and fruits including carrots, kale, bell pepper, squashes, sweet potatoes, pears and apples. This demonstration showed and documented the benefits and viability of the new technology on a commercial scale, in energy savings and reduction in environmental pollution, while producing new healthy snacks with desirable texture, color and flavor at a reduced cost.

The team successfully:

- Developed and designed a commercial production facility with SIRDBHAD technology with a vegetable and fruit processing capacity of 70 kg per hour with an annual capacity of 133,500 kg.
- Optimized the SIRDBHAD processing and operation to produce high quality products by quantifying the product quality (crispness, color, nutrients and flavor) and maximizing the energy efficiency by quantifying the energy consumption in each processing step; and
- Disseminated information on this technology benefits to snack foods processors and related organizations to enhance overall industry energy savings and make the products available in the global marketplace.

# CHAPTER 2: Laboratory Study of Technology

To design the commercial scale SIRDBHAD system for different vegetable and fruit snacks, it is very important to determine the design parameters, including the infrared (IR) drying temperature, IR drying time, hot air temperature, air flow rate and hot air-drying time. Laboratory studies on SIRDBHAD of carrots and kale were performed to identify these design parameters and determine the quality of SIRDBHAD dried products.

## Carrots

### Materials and Methods

#### Sample Preparation

Locally available fresh carrots (Daucus carota L.) with an initial moisture content of 87.0 grams (g)/100 g (wet basis) were used for the study. The sample was washed and peeled followed by cutting into 1 millimeter (mm) thick slices with a diameter of 25 mm. The carrot slices were treated with IR heating immediately after cutting.

#### Infrared Blanching System

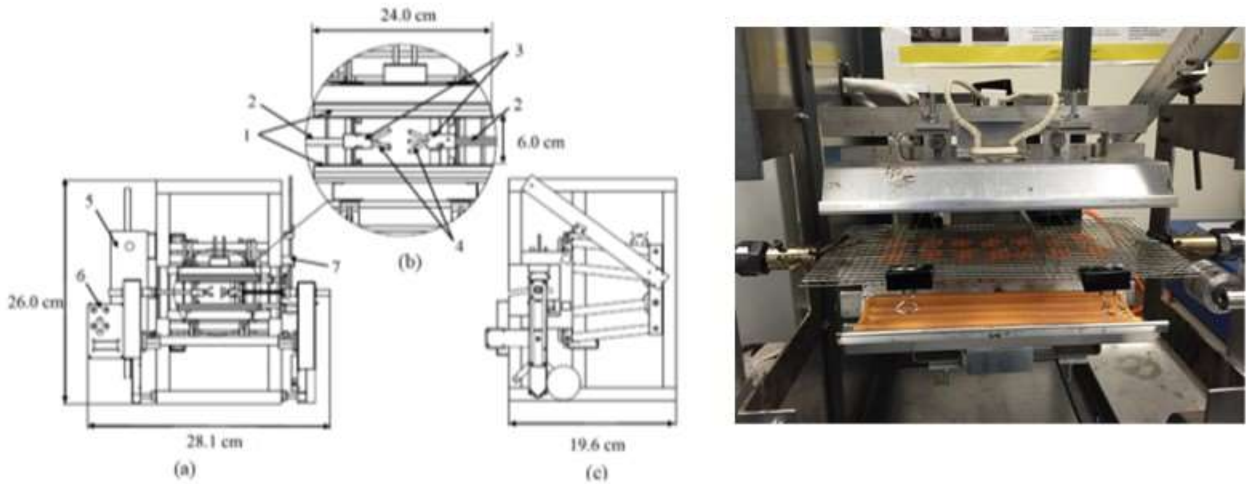
A laboratory scale IR heating system consisting of two 239 volt IR emitters (with surface areas of 245×60 mm) of 1,000 watts capacity (6 kilowatts per square meter [kw/$m^2$]) manufactured by Ceramicx Ireland Ltd, Cork, Ireland were used for IR heating/blanching. The emitters emit radiation at wavelengths of 2 to 10 µm. Each emitter has an aluminum wave-guard attached to distribute radiation intensity uniformly and minimize the heat loss. The schematic drawing of the IR heating system is shown in Figure 1. The IR emitters were fixed to a frame connected to a metallic arm. The vertical distance between the IR heaters could be adjusted by tightening and loosening the nut on the space bar. A pair of custom-designed holders with a set of fingers and a stainless-steel wire mesh was placed on the fingers to hold the carrot slices.

#### Simultaneous Infrared Dry-Blanching and Dehydration Test

*IR Blanching*

The power level of 552 watts was chosen for the experiments based on the preliminary experiments. A single layer of fresh carrot slices was spread uniformly on the stainless-steel wire mesh and exposed to IR radiation with different intensities and durations (110, 130, 150 seconds [s]). The intensities were achieved by adjusting the distance between the samples and the emitter (70, 75 and 80 mm). The chamber was preheated to the required temperature before blanching. IR heat was applied continuously.

**Figure 1: The Schematic Diagram and Photo of the Infrared Heating System**




**(a) Front view; (b) Detailed view of the sample holder setup and (3) Side view, including 1. Electric IR emitter; 2. Rotating shafts; 3. Sample holders; 4. Fingers of the sample holders; 5. IR power regulator; 6. Rotational speed regulator of the sample holders; 7. Screws to adjust the distance between the IR emitters.**

*Source: University of California, Davis*

### *Hot Air Drying*

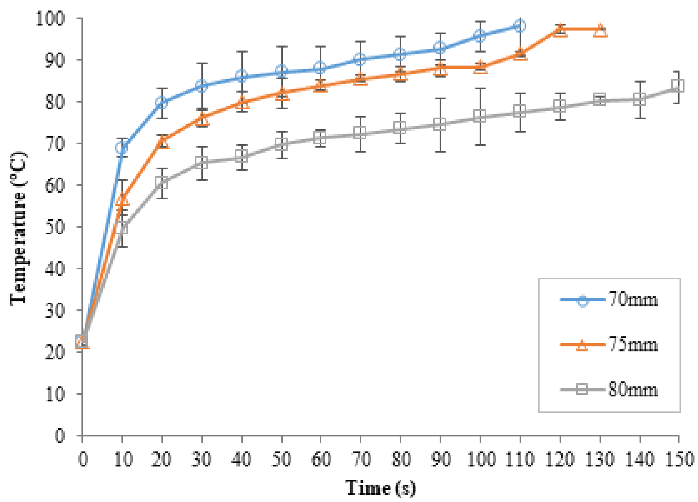
Blanched carrots using IR heating and unblanched carrots were dried using a hot-air (HA) drier at 60, 70 and 80°C, respectively. Samples were drawn at regular intervals to measure the moisture contents. The slices were dried to the moisture content of ~5% (wet basis, [w.b.]). The dehydrated samples were packed in aluminum foil bags and stored in the desiccator at 25°C. Drying experiments were carried out with two exact copies.

## Drying and Quality Characteristics of Carrots

### Surface Temperature and Moisture Reduction

The surface temperatures of the carrot slices were measured using a T-type thermocouple (HH147, Omega Engineering Inc., Stamford, CT, USA; response time 0.15 s) inserted just beneath the surface of the slices. Data were recorded every 10 seconds with a data logger. Temperature measurements were repeated five times for each processing condition and the average values are reported in Figure 2. IR blanching of carrot slices was performed by heating the slices to a temperature of 65°C. It took 10, 20 and 40 s to reach 65°C for IR blanching with the carrot slices placed at distances of 70, 75 and 80 mm from the IR emitters, respectively. Placing the carrot slices at different distances from the IR emitters resulted in different radiation intensities on the slices. Higher radiation intensity resulted in faster increase of surface temperature than lower radiation intensity. The temperature of the thin carrot slices increased rapidly in the beginning of the heating period due to the small dimensions, low mass of the slices and availability of free water on the surface. As IR heating continued, a significant amount of radiation energy was used in evaporating the water and increasing slice temperature, resulting in a reduced rate of increase in the product temperature. When most of the surface moisture had been evaporated, the surface temperature and the heating rates increased again.

**Figure 2: Surface Temperatures of Carrot Slices During Infrared Blanching With Different Intensities**




*Source: University of California, Davis*

The moisture contents of the raw, blanched and dried carrots were determined according to the oven drying method at 105°C and expressed as percentage wet basis. Each result was averaged from three replicates. During IR heating of carrots, as the moisture contents decreased to around 70%, the carrot slices under all three treatments started to burn (char). Therefore, the longest treating times selected for the three conditions were 110, 130 and 150 s and the corresponding highest temperatures were 98.1, 97.4 and 83.5°C, respectively. Due to higher temperature of carrot slices (98.1°C) at the distance of 70 mm, the initial temperature of carrot slices would be higher when they were transferred to HA drying. In addition, the moisture contents and residual peroxidase (POD) activity of the samples with different intensities were not significantly different (Table 1). Therefore, 70 mm was chosen for following HA drying experiments as it had the shortest drying time resulting in higher energy efficiency.

## Moisture Reduction and Drying Kinetics

The moisture content data obtained during IR and hot air drying of carrot slices were used for modeling of drying kinetics. In this study, the Midilli drying model (MR = a * exp(-kt n) + bt) was used to describe the drying curves of thin layers of dried carrots at various processing conditions (Midilli et al., 2002). The coefficient of determination ($R^2$)

and root mean square error (RMSE) were calculated to determine the performance of the models (Doymaz, 2004). The moisture ratio (MR) could be simplified as:

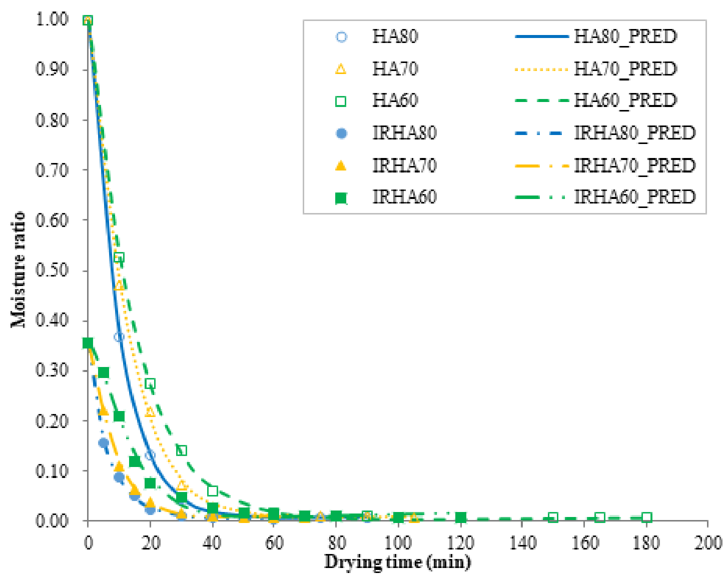
$$MR = \frac{m - m_e}{m_0 - m_e}$$

where $m_0$ is the initial moisture content (g water/g dry basis); $m_e$ is the equilibrium moisture content (g water/g dry basis); and $m$ is the moisture content (g water/g dry basis) during drying at various times. Since the values of $m_e$ are relatively small compared to $m_0$ and $m$, $(m - m_e)/(m_0 - m_e)$ is simplified to $m/m_0$, as follows:

$$MR = \frac{m}{m_0}$$

The drying curves of HA dried carrot slices with and without IR blanching at different temperatures are shown in Figure 3.

**Figure 3: Hot Air Drying of Carrots**




**Experiment measured (symbols) and Midilli model regressed (lines) moisture contents of carrot slices at different heating times under various processing conditions (HA60, HA70 and HA80 indicate hot air (HA) drying at 60, 70 and 80°C; IRHA60, IRHA70 and IRHA80 indicate sequential infrared (IR) blanching and hot air drying at 60, 70 and 80°C.)**

*Source: University of California, Davis*

These drying curves were similar to the typical drying curves of fruits and vegetables. The moisture ratios of the products decreased exponentially with diminishing drying time in all cases, as expected. Differences among the moisture ratios increased gradually as drying continued. IR blanched samples had 14.5 % lower initial moisture than the unblanched samples. As shown in Figure 3, the time taken to reduce the moisture content of carrot slices from the initial moisture (~87 percent) to a final desired moisture (~5 percent) was 120+1.83, 60+1.83 and 45+1.83 minute for IR blanching (1.83 min) and HA drying at 60, 70, and 80°C, respectively. Increasing the drying temperature resulted in an increase in the drying rate, because higher temperature can lead to a higher value of moisture diffusivity and provide a larger water vapor pressure deficit (Goula & Adamopoulos, 2010). Combining IR blanching and HA drying required less time (reductions of 32.3percent, 41.1 percent and 45 percent) reaching the final desired moisture contents, as compared to HA drying alone at temperatures of 60, 70 and 80°C, respectively. The results agree with a previous study, where the time of sequential IR blanching and HA drying was ~22 percent less than that of sequential water blanching and HA drying at 80°C (Vishwanathan et al.,2013). Overall, the results showed the benefits of IR blanching. Reduction in drying time could be attributed to lower moisture contents of IR blanched samples. In addition, the initial surface temperature of the blanched samples was higher, which might have led to the shorter drying time. Therefore, an IR drying unit could be added in front of current conventional drying systems to take advantage of improved overall drying rate. In addition, reduced drying time can result in high quality dried products as longer drying time could lead to flavor, color and nutrient loss in the products (Devahastin & Niamnuy, 2010).

**Peroxidse Enzyme Activity**

Peroxidase (POD) is one of the most heat resistant enzymes present in many fruits and vegetables, making it a common enzymatic indicator for blanching (Güneş & Bayindirli, 1993; Sheu & Chen, 1991). When POD is inactivated, most of the other enzymes in fruits and vegetables might not survive (Halpin & Lee, 1987). To determine the POD enzyme activity, the fresh and treated carrot slices were homogenized with chilled 0.1 Molar (M) phosphate buffer (pH 6.0) in the ratio of 1:4 for 3 minutes. The suspensions were centrifuged at 5,000 revolutions per minute (rpm) for 30 minutes at 4°C (5840R, Eppendorf, Germany). The supernatants were filtered through medium-fast filter paper and kept on ice until analyzed. The activity of POD was measured according to the previously used procedures (Morales Blancas, Chandia & Cisneros Zevallos, 2002). A 60 microliter (μL) homogenate sample was incubated at room temperature with 1.0 milliliter (mL) of a substrate solution containing 5 milliMoles (mM) guaiacol (in 0.1 M sodium phosphate buffer, pH 6.0) and 10 mM $H_2O_2$. The POD substrate solution was prepared daily. Absorbance increase at 500 nanometers (nm) was monitored for up to 2 minutes with a UV-Vis-NIR spectrophotometer (UV-3600, Shimadzu, Japan), and the slope of the curve was used to determine activity. Each extract was prepared in duplicate and two copies were run for each extract. One unit of POD activity was defined as an increase of 0.001 unit of absorbance per minute. The POD activity was expressed on dry weight basis for comparison. Fresh carrots were used as the control and the values were expressed in terms of percentage. The residual enzyme activities were calculated as:

$$\text{Residual enzyme activity (\%)} = \frac{A_t}{A_0} \times 100$$

Where, $A_t$ is the remaining enzyme activity (unit/mg of protein) obtained after treatments, and $A_0$ (unit/mg of protein) is the enzyme activity of fresh carrot slices.

After IR blanching, the residual POD activity for the three treatments in the study were 25.6, 25.4 and 24.4 percent, respectively, for carrot slices placed at a distance of 70, 75 and 80 mm from the IR emitters, as shown in Table 1. The color was tested to confirm the quality of blanched carrot slices.

**Table 1: Results of the Blanched Carrot Slices**

| Measurement | Treatment 1 | Treatment 2 | Treatment 3 |
|---|---|---|---|
| Distance between the emitter and samples | 70 mm | 75 mm | 80 mm |
| Time (s) | 110 | 130 | 150 |
| Surface temperature (°C) | 98.1±6.8 | 97.4±0.3 | 83.5±3.7 |
| Moisture content (%, wb) | 72.1±1.4 | 69.2±1.2 | 68.5±3.3 |
| Residual POD activity (%) | 25.6±0.5 | 25.4±0.7 | 24.4±3.8 |

**Blanching time, final surface temperatures, moisture contents and residual peroxidase (POD) activity of infrared (IR) blanched carrot slices.**

*Source: University of California, Davis*

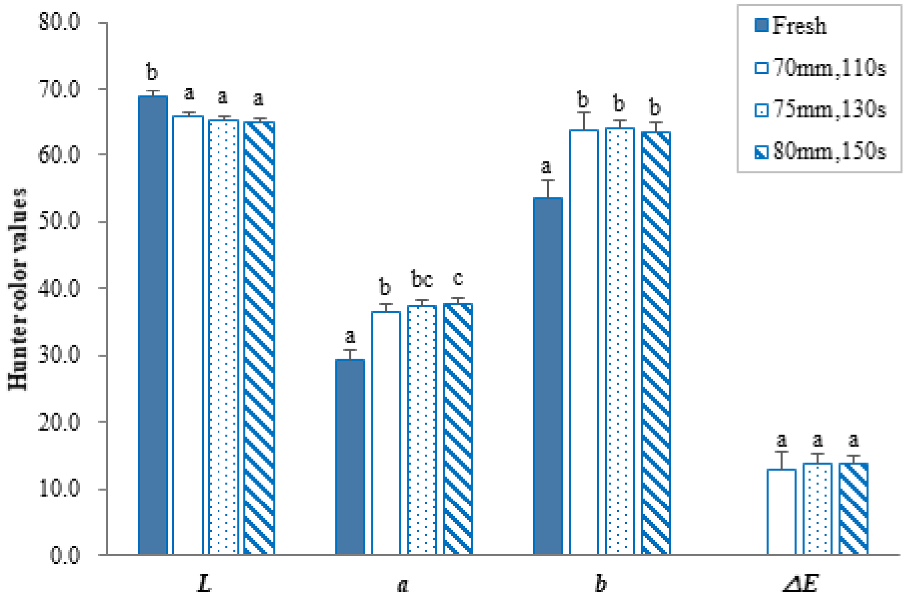
## Color Measurement

The color of carrot slices was measured just before and immediately after blanching and drying treatments using a colorimeter (CR 400, Minolta, Japan) to obtain the color values (L, a and b). The L value represents the darkness to lightness gradation; the a value represents the greenness to redness values and the b value represents the blueness to yellowness values. The overall color change (ΔE) was evaluated as:

$$\Delta E = \sqrt{(L_0 - L)^2 + (a_0 - a)^2 + (b_0 - b)^2}$$

Where subscript "zero" refers to the color reading of fresh carrot slices used as the control. A larger ΔE value indicates greater color change from the control sample. The color change of IR blanched samples are shown in Figure 4.

**Figure 4: Color Change of Infrared Blanched Samples at Different Intensities and Heating Times**




**Different letters indicate statistical difference at different intensities (P<0.05).**

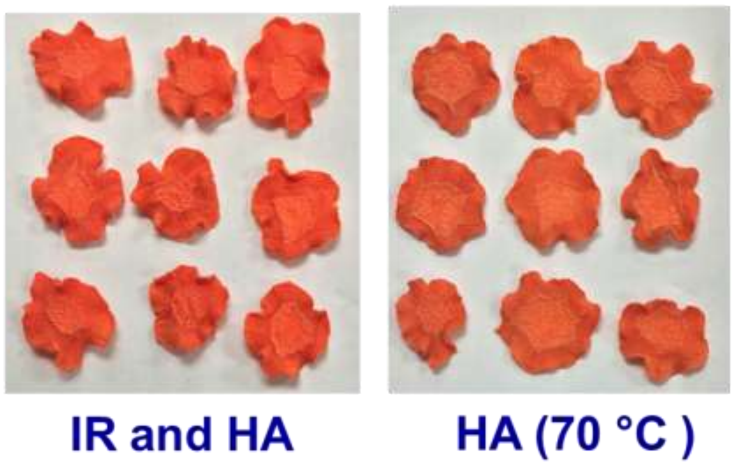
*Source: University of California, Davis*

Compared with fresh carrots, the L value (brightness) of IR blanched carrots decreased and the a and b values (redness and yellowness) increased significantly. The change in L value corresponds to enzymatic browning due to the residual polyphenol oxidase (PPO) activity in carrot slices in the earlier time (Ndiaye and others 2009). In addition, non-enzymatic browning also affects the L value (Wu et al., 2014), and the change in color values was probably not only due to browning, but could also be attributed to effects such as shrinkage and changes in reflective characteristics during dehydration (Baysal, Icier, Ersus & Yıldız, 2003). The L, b and ΔE values were not significantly different among the different processing treatments. The a value increased when the heating distance, however, no obvious difference was observed.

After dehydration, the carrot slices blanched with IR and dried by HA at 70°C and 80°C showed lower POD activity. According to the results of color change for dried carrots, IR blanching can maintain the carrot color during HA drying to produce more desirable products. And it will continue to benefit the color preservation during storage. Therefore, it would be more effective to protect the quality of carrot chips if IR blanching is combined with HA drying at 70 and 80°C.

The overall color attributes of carrot slices dried by two processing methods (HA drying and sequential IR blanching and HA drying) were distinguishable based on both visual and instrumental assessments of color (Figures 5 and 6). The L, a, and b values of fresh carrot slices were found as 70.28, 26.65 and 58.32, respectively. There are significant differences in the L, a and b values between the sequential IR blanched and HA dried samples and solely HA dried samples at the same temperature (P<0.05). The color change during drying may be related with various factors including thermal and oxidative destruction of carotenoids and enzymatic or nonenzymatic browning (Nahimana & Zhang, 2011).

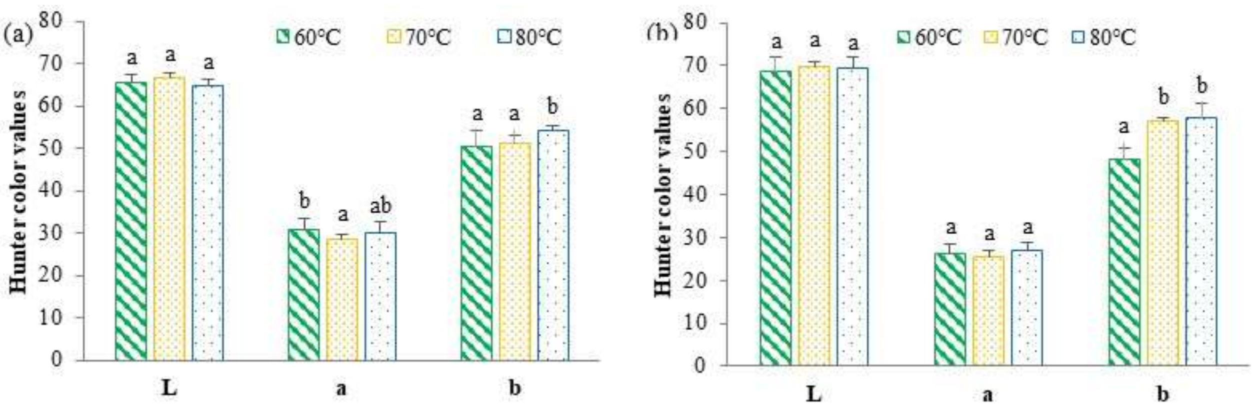
**Figure 5: Carrot Slices After Infrared and Hot Air Drying**




**After (a) sequential infrared blanching and hot air (IR+HA) drying and (b) hot air (HA) drying.**

*Source: University of California, Davis*

**Figure 6: Color Change of Carrot Slices After Infrared and Hot Air Drying**




**Color change of carrot slices after (a) sequential infrared blanching and hot air (IR+HA) drying and (b) hot air (HA) drying in different temperatures.**

*Source: University of California, Davis*

A significant whitening process was observed in unblanched-dried samples with higher whitening index (WI) values. Whitening resulted from the production of a protective layer known as 'white blush' caused by the dehydration, enzymatic activity of enzymes such as lipoxygenase and POD, and by lignification, which is also an enzyme-stimulated reaction (Cisneros-Zevallos, Saltveit & Krochta, 1995; Rocha, Ferreira, Silva, Almeida &

Morais, 2007). Whitening can lead to the pale red color of dried carrot, which is undesirable. L values increased during drying, which could be related to whitening of the samples. The unblanched and dried samples had higher L values than those of IR blanched carrots since the enzymes were still active during the initial stage of HA drying (Hiranvarachat, Devahastin & Chiewchan, 2011). Due to the reduction in enzyme activity, the L value of the IR blanched and HA dried carrots was lower, and the dried carrot slices showed a desirable bright red color. The results of color change were similar with the IR dry blanched mangos (Guiamba, Svanberg & Ahrné, 2015). Compared with the fresh unblanched carrots, it was found that IR blanching increased the a values. It indicates that IR blanching can contribute to redder dried samples. In addition, changes in the a and b values were probably not only due to nonenzymatic browning as a consequence of high surface temperature during IR processing, but could also be attributed to effects such as shrinkage and changes in the reflective characteristics during HA drying (Baysal et al., 2003). Furthermore, the improved red color might be due to the increased concentration of pigments in all the pretreated carrots due to the increased availability of carotenoid pigments caused by the deterioration of both crystalline carotenoid complexes and the pectin in carrot cell walls (Alam, Gupta, Khaira & Javed, 2013; Micheli, 2001). Moreover, the color of dried samples with IR treatment was maintained for a longer time (data not shown). This indicates that IR treatment could be used to stabilize the red color in the dried carrots.

**Shrinkage**

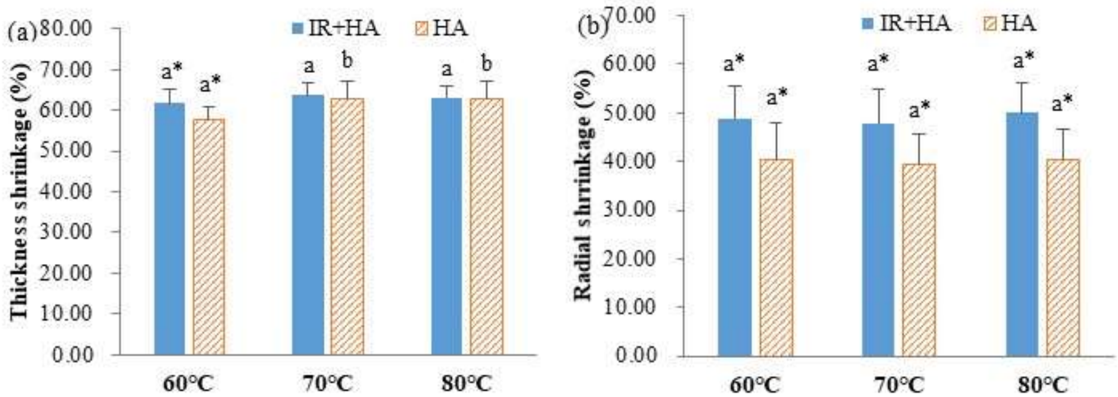
The thickness and diameter of the fresh and dried samples were measured using a digital caliper (Harbor Freight Tools, Camarillo, California). The percentage shrinkage was determined based on the initial and final thickness and diameter values.

$$\text{Shrinkage (\%)} = \left[1 - \left(\frac{d}{d_0}\right)\right] \times 100$$

Where, $d_0$ is the diameter or thickness (mm) of the fresh carrots and d is the diameter or thickness (mm) of the carrots after drying.

Ten pieces of carrot samples from each drying treatment were measured and the average thickness and radial shrinkage were reported. The thickness and radial shrinkage of carrot slices caused by different drying treatments are shown in Figure 7. There was no significant difference in the thickness shrinkage observed among the sequential IR blanched and HA dried samples, except for the HA dried samples at 60°C. This indicates that IR blanching results in small but insignificant shrinkage on the thickness of the slices. The shrinkage during drying is caused by stress resulting from moisture removal (Ketelaars, Jomaa, Puiggali & Coumans, 1992). As for the radial shrinkage, no significant difference was observed among different temperatures for both the sequential IR blanched and HA dried samples and solely HA dried samples because the wire mesh used to hold the samples reduced the radial stress in this study. However, the sequential IR blanched and HA dried samples were observed to shrink more than the HA dried samples at the same temperature (P<0.05). This is because IR blanching quickly removed the moisture content of carrot, which increased the stress.

**Figure 7: Carrot Thickness and Shrinkage after IR and HA Drying**




**(a) Thickness and (b) radial shrinkage of carrot slices after sequential infrared blanching and hot air (IR+HA) drying and hot air (HA) drying at different temperatures. *indicates statistical difference between the IR+HA and HA dried samples (*P*<0.05); Different letters indicate statistical difference in the different temperatures (*P*<0.05).**

*Source: University of California, Davis*

## Texture Analysis

For fruit and vegetable chips, a crispy texture is always expected because crispness is associated with freshness and high quality (Troncoso & Pedreschi, 2007). A recommended assay to study the texture of fried and dried carrot is the puncture test, which measures the initial slope and the maximum force at the breaking point from the force curves (Pedreschi & Moyano, 2005; Shyu, Hau & Hwang, 2005). A puncture test was performed on the dried carrot slices using a TA-XT2i Texture Analyzer (Stable Micro Systems Ltd., Vienna Court, Surrey, UK) to measure the textural properties (Hua, Wang, Yang, Kang & Yang, 2015). The cylinder penetrometer probe (2-mm diameter) was passed through the slices with the test parameters of 5 mm/second of pre-speed, 5mm/second of test speed, 10 mm/s of post-speed, and 20 g of trigger. The data collected included the maximum force and the slope of the force curve from the beginning of the compression to the fracturability point (the first peak of force). Texture analysis was performed for ten samples from each treatment and the average value was reported. The initial slope of the force curve is related to the stiffness, and he puncture force represents the hardness of a product's surface (Salvador, Varela, Sanz & Fiszman, 2009). The initial slope is positively correlated with crispness, while increase in the maximum force indicates less crispness (Pekke et al., 2013; Sulaeman, Keeler, Giraud, Taylor & Driskell, 2003). In addition, the initial slope was recommended as a measure of crispness since it presented less variability than the maximum force of break (Pedreschi et al., 2005). Therefore, in this study both the initial slope and the maximum force were used as indicators of crispness for the dried carrot chips. Table 2 shows the initial slopes and the maximum forces of carrot chips obtained in the present study.

**Table 2: Crispness and Peroxidase Activity of Carrot Slices After Infrared and Hot Air Drying**

| Temp | Initial slope (kg/s) IR+HA# | Initial slope (kg/s)HA† | Maximum force (kg)IR+HA | Maximum force (kg) HA | Residual POD activity (%) IR+HA | Residual POD activity (%) HA |
|---|---|---|---|---|---|---|
| 60°C | 1.86±0.54a* | 1.28±0.32a* | 0.406±0.103a* | 0.293±0.083a* | 30.73±0.43b* | 52.56±1.74c* |
| 70°C | 1.94±0.50a* | 1.54±0.25a* | 0.264±0.064b | 0.243±0.093a | 15.31±0.07a* | 26.86±0.52b* |
| 80°C | 2.11±0.56a* | 1.60±0.32a* | 0.256±0.070b | 0.228±0.054a | 14.00±0.02a | 13.53±0.28a |

**# IR+HA: Sequential infrared blanching and hot air drying; † HA: Hot air; * indicates statistical difference between the IR+HA and HA dried samples (*P*<0.05); Different letters indicate statistical difference in the different temperatures (*P*<0.05).**

*Source: University of California, Davis*

Although there was no significant difference in the slope values for different temperatures from 60 to 80°C (P>0.05), the increasing trends were observed with increased drying temperatures for both IR blanched and unblanched samples. Nonetheless, the IR blanched samples showed larger slope values than those of the unblanched samples at the same temperature which means that the IR processing can improve the crispness of carrot slices. As for the maximum force, similar results were obtained. No significant difference was observed among dried samples at different temperatures or between the unblanched and blanched samples at the same temperature, except for the samples dried at 60°C. However, compared with the unblanched samples, the maximum force of the blanched samples at the same temperature decreased. This indicates that the hardness of IR blanched samples was lower and they became crispier. During HA drying, liquid diffused to the surface of the carrots from the interior and carried solutes with it. As the surface moisture evaporated, solutes concentrated and precipitated, leaving a hard and dry skin. Less case hardening occurred with IR processing because the IR can penetrate into the thin slices and heat inside, resulting in in-situ vaporization of water, without carrying dissolved solutes with it to the surface (Lin, Durance & Scaman, 1998).

POD is one of the most heat resistant enzymes present in many fruits and vegetables, making it a common enzymatic indicator for blanching (Güneş & Bayindirli, 1993; Sheu & Chen, 1991). When POD is inactivated, most of the other enzymes in fruits and vegetables might not survive (Halpin & Lee, 1987). After IR blanching, the residual POD activity for the three treatments in this study were 25.6, 25.4 and 24.4percent, respectively, for carrot slices placed at distances of 70, 75 and 80 mm from the IR emitters .It was reported that pulsed electric field pretreatment can only reduce 30–50 percent of the POD activity. Also, there were no color differences between pulsed electric field (PEF)-pretreated and water blanched carrots before and after rehydration (Gachovska, Simpson, Ngadi & Raghavan, 2009). Therefore, the IR dry-blanching provided better POD inactivation than PEF and water blanching.

**Vitamin C and Total Carotenoid Retention**

Vitamin C (ascorbic acid) is the most heat altered among all the vitamins, and the extent of vitamin C loss during thermal processing is influenced by temperature, presence of oxygen, and drying time (Davey et al., 2000). The vitamin C content of the carrot slices was determined by titration of filtrate against 2, 6-dichlorophenolindophenol and expressed on dry weight basis (Soysal, Söylemez & Bozoğlu, 2004). Fresh carrots were used as control. The retention of vitamin C was calculated as:

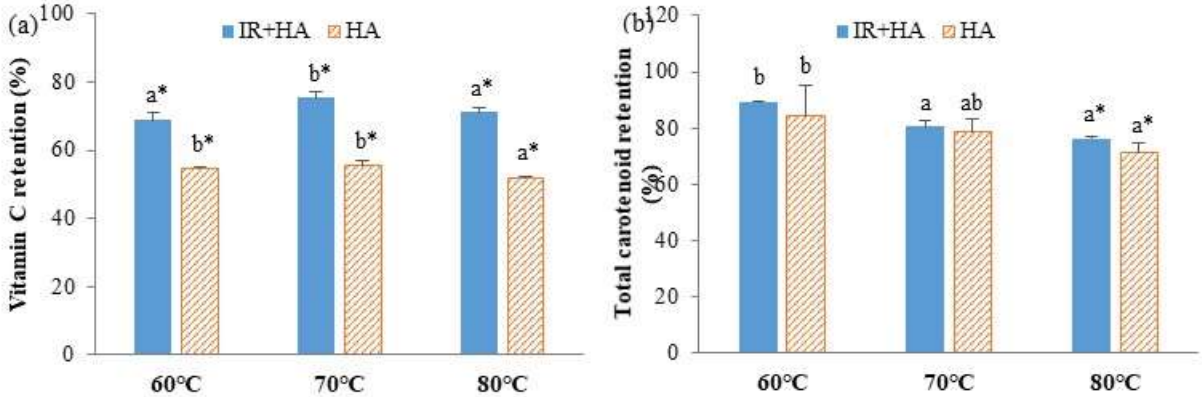
$$\text{Retention of vitamin C (g/100g)} = \frac{V_t}{V_o} \times 100\%$$

Where, $V_t$ is the vitamin C content of the dried carrots and $V_0$ is the vitamin C content of fresh carrots.

The total carotenoid content was measured using the modified method (Ahmed, Sorifa & Eun, 2010) with 5 g of fresh carrots or 0.5 g of dehydrated carrots were extracted with a mixture of hexane and acetone (7:3, 25 mL) and 3-4 g quartz sand in a mortar and pestle. The extractions were repeated until the residue became colorless. After filtration, the filtrate was combined in a separatory funnel and washed with 50 mL distilled water. The water phase was discarded and anhydrous $Na_2SO_4$ was added as desiccant. The hexane phase was transferred to the volumetric flask and brought to volume with hexane. The concentration of the total carotenoids in the solution was determined from its absorbance at 450 nm. External calibration with authenticated β-carotene standards solutions (0.5–10 μg/mL) was used to quantify the carotenoid contents in the solutions.

Vitamin C and total carotenoid retention of carrot slices after sequential infrared blanching and hot air (IR+HA) drying and hot air (HA) drying at the different temperatures are shown Figures 8a and 8b, respectively.

**Figure 8: Vitamin C Retention and Total Carotenoid Retention of Carrot Slices After IR and HA Drying**




**(a) Vitamin C retention and (b) total carotenoid retention of carrot slices after sequential infrared blanching and hot air (IR+HA) drying and hot air (HA) drying at different temperatures. * indicates statistical difference between the IR+HA and HA dried samples (*P*<0.05); Different letters indicate statistical difference in the different temperatures (*P*<0.05).**

Retaining vitamin C in the sequential IR blanched and HA dried samples was significantly higher than the HA dried samples without IR blanching at the same temperature (*P*<0.05), because the enzymes such as ascorbic acid oxidase (AAO) and PPO were inactivated during IR blanching (Munyaka, Makule, Oey, Van Loey & Hendrickx, 2010) and the heating time was reduced. Carrot slices dried using sequential IR blanching and HA drying at 70°C retained higher vitamin C content (75.33 percent) compared with those dried using HA alone at temperatures of 60°C (68.90 percent) and 80°C (71.06 percent). This was because the hot air drying at 60°C required longer time, which caused the degradation of vitamin C, while the higher temperature (80°C) might have accelerated the degradation of vitamin C (Frias, Peñas, Ullate & Vidal-Valverde, 2010a). These results agreed with the previous studies which showed that an increase in drying temperature could result in lower retention of vitamin C in HA and IR dried carrots (Frias et al., 2010a; Wu et al., 2014). Since vitamin C is a water-soluble micronutrient, water blanching is expected to reduce its content due to leaching into the blanching water. IR blanched peas were reported to have comparable retention of vitamin C over water blanched samples (Vishwanathan et al., 2013). Thus, IR blanching helped to maintain nutritional quality and even flavor and taste compared to water blanching. Consequently, the results showed that the combination of IR blanching and HA drying yielded better product quality in terms of water soluble nutrients, such as vitamin C.

Oxidation of unsaturated carotenoid molecules and isomerization of trans-carotenoids to the light colored cis-forms help lose carotenoids when exposed to air and high temperature (Cui, Xu & Sun, 2004). Deterioration and isomerization of carotene not only affect the color and flavor of foods, but also compromise the nutritional quality in terms of provitamin A activity and antioxidant capacity (Pesek & Warthesen, 1990). In this study, as the temperature increased, the total carotenoid contents for IR blanched and unblanched carrot slices decreased from 89.12 percent to 76.28 percent and from 84.16 percent to 71.04 percent, respectively. This indicates that raising the drying temperature increased the loss of betacarotene. Moreover, the carotenoids in carrots are relatively heat stable during drying, compared with vitamin C (Lin et al., 1998). A similar observation of carotenoid degradation of HA dried carrot slices without blanching (3mm thickness) was reported. The final total carotenoid contents were found as 79%, 76%, 74%, and 71% for 50-80°C, respectively (Goula et al., 2010). In addition, in this study, it was found that the total carotenoid retentions in carrot slices dried at 70 and 80°C were not significantly different between the IR blanched and unblanched carrot slices. The reason may be that the drying temperatures used in those cases were already higher than the degradation temperature of β-carotene (55°C) (Hiranvarachat et al., 2011; Şanal, Bayraktar, Mehmetoğlu & Çalımlı, 2005). Furthermore, there was no significant difference in total carotenoid contents between the IR blanched and unblanched dried samples at the same temperatures of 60 and 70°C. This indicates that the IR blanching did not cause carotenoid degradation at 60 and 70°C. In addition, the total carotenoid contents of the blanched and dried samples were significantly higher than those of the unblanched and dried samples at 80°C, because longer HA drying at higher temperature of 80°C might have caused more carotenoid degradation. During water blanching, some substances which are responsible for stabilizing the carotenoids are degraded or leached. Therefore, carotenoids become more susceptible to oxidation after water blanching. (Frias, Peñas, Ullate & Vidal-Valverde, 2010b). Furthermore, more total carotenoid retention can be obtained by IR blanching rather than water blanching. In summary, the IR blanching partially inactivated the enzymes and protected the carotenoids from deteriorating. It shortened the drying time which also reduced the degradation of the carotenoids as well.

This lab study with carrots demonstrated that IR blanching could shorten the drying time of carrot slices due to the reduction of the initial moisture contents of the dried samples (14.5%). Carrot samples dried after IR blanching resulted in consistently redder products with low remaining POD activity. The sequential IR blanched and HA dried carrot chips were crispier than unblanched HA dried chips and the IR blanching improved the vitamin C retention and higher total carotenoid content. IR blanching prior to HA drying is a potential method for improving sensory and nutritional quality of fried products without the extensive water usage.  The study provided the information and data related to the IR drying temperature and heating time required to achieve blanching and also hot air temperature and time required to produce crispy and redder carrot chips with high retention of vitamin C and carotenoid content.

# Kale

To determine design parameters for the SIRDBHAD system which would make it suitable for drying thin and highly nutritious leafy greens, IR and hot air drying of kale was performed and the quality parameters of dried kale were determined.

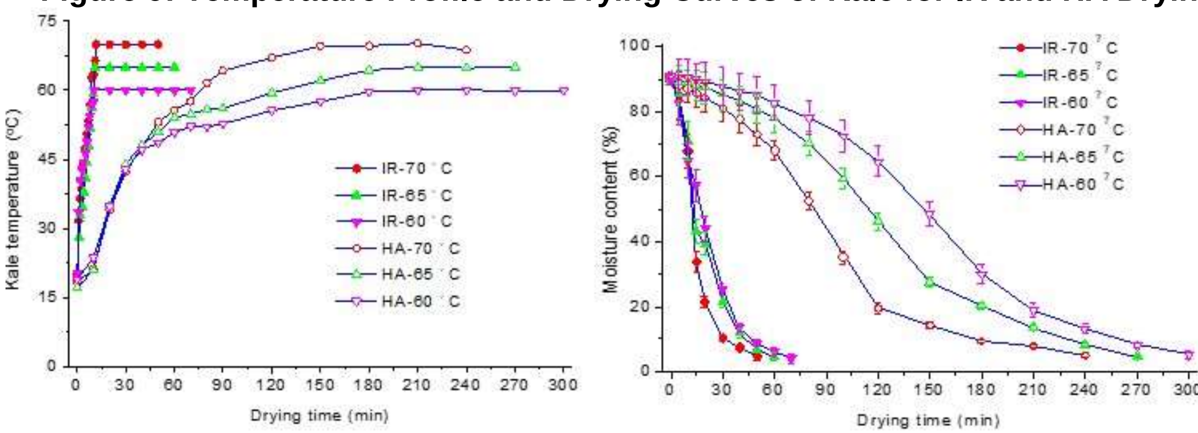
## Kale Samples

Fresh kale was purchased from a local market. Before starting each experiment, fresh kale leaves were washed, stemmed, and shredded into pieces each with a size of 3 cm x 5 cm. The kale pieces were then dried using IR and hot air. The average initial moisture content of the fresh kale pieces was found to be 89.16 percent (wet basis).

## Drying Procedure

Fresh kale shredded into about 3 x 5 cm pieces were dried in the sequential IR and hot air (SIRHA) dryer using infrared heating at an intensity of 4000 W/m$^2$ at the product temperatures of 60°C, 65°C and 70 °C, respectively. The loss in the weight of kale samples was then determined by weighing the product at regular intervals until the moisture content reached about 5%. Kale dried using hot air at air temperatures of 60°C, 65°C and 70 °C, respectively, produced a moisture content of about 6%. The temperature profile and drying curves of kale for IR and hot air drying are shown in Figure 9.

**Figure 9: Temperature Profile and Drying Curves of Kale for IR and HA Drying**




*Source: University of California, Davis*

## Drying and Quality Characteristics of Kale

### Temperature and Moisture Loss

For the IR process, the temperature profile of the kale samples showed that the temperature of the product increased sharply as soon as drying started. The samples reached the set IR drying temperature within 10 minutes and then remained at the same temperature throughout the drying process. For the hot air drying process, the temperature of kale samples gradually dropped during the drying time. The drying curves of kale showed that IR drying at 60°C, 65°C and 70°C, took 70, 60 and 50 minutes, respectively, to dry the kale to a moisture content of 5 percent. Hot air drying at the hot air temperatures of 60°C, 65°C and 70°C required 300, 270 and 240 minutes, respectively, to dry the kale to 5 percent moisture content. IR drying resulted in significant reduction in drying time compared to hot air drying. IR drying reduced the drying time by 190 minutes or 79 percent, 210 minutes or 78 percent, and 230 minutes or 77 percent,at 60 °C, 65 °C, and 70 °C, respectively, compared to hot air drying at the same drying temperatures.

### Color of Dried Kale

For color measurement, the dried kale pieces were ground to powder using a small-scale blender and made into particles of less than 100 mesh screen and subjected to colorimeter measurement as was used for carrots as described in the previous section. A sample of 2 g of kale powder was packed in a 5 centimeters (cm) diameter plastic Petri dish, the color measurement performed,s and values for L*, a*, b* and $\triangle E$ were obtained. Five measurements for each sample were performed and average values are reported in Table 3.

**Table 3: Color Change of Kale Pieces After Infrared and Hot Air Drying at Different Temperatures**

| Drying condition | L | a | b | ΔE |
|---|---|---|---|---|
| Fresh Kale | 44.55±4.33[a] | -15.20±1.82 [d] | 21.83±2.69 [e] | 55.60±5.30[d] |
| IR 60 °C | 44.06±0.02[a] | -7.74±0.00[a] | 11.52±0.02[a] | 51.98±0.02[c] |
| IR 65 °C | 45.39±0.42[a] | -7.73±0.09[a] | 11.56±0.14[a] | 50.69±0.41[b] |
| IR 70 °C | 45.83±0.45[a] | -8.02±0.89[b] | 12.57±0.08[b] | 50.48±0.58[b] |
| HA 60 °C | 48.56±1.22[c] | -8.19±0.02[c] | 14.18±0.01[d] | 48.13±1.16[a] |
| HA 65 °C | 46.28±0.31[ab] | -8.04±0.04[bc] | 13.34±0.07[c] | 50.11±0.29[b] |
| HA 70 °C | 45.65±0.17[a] | -7.98±0.03[ab] | 13.00±0.30[bc] | 50.68±0.08[b] |

*Source: University of California, Davis*

The color values (L, a, b) nearest to those of fresh kale pieces were obtained for the IR dried kale samples. L values showed that the kale samples dried by IR had a darker green color than those dried by hot air although both the IR dried and hot air dried kale samples had no significant difference in L value with that of fresh kale, except for the hot air dried samples at 60°C. This may have been due to prolonged drying for 230 minutes during which the color became light or faded. The a values increased during drying while the b values decreased due to the combined effect of temperature and drying time.

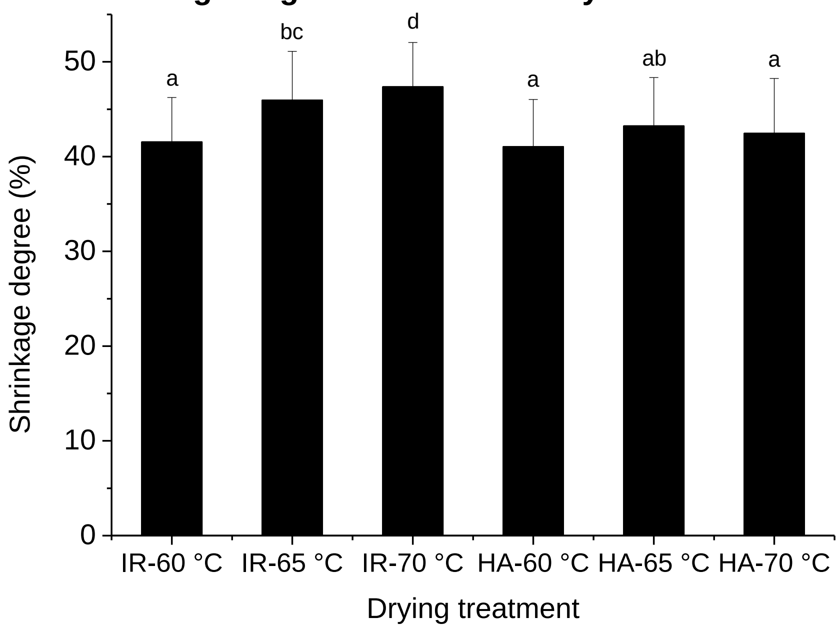
### Shrinkage

The degree of shrinking during drying was calculated by determining the volume of kale before and after drying. Kale volume was measured using the quinoa replacement method described by Hallén, İbanoğlu, & Ainsworth (2004) with some modification. Fresh or dried kale pieces were put in a metallic container with known volume (VC). The container was topped up with quinoa, and then the quinoa and kale pieces were removed and separated. The volume of the quinoa was noted (VR). The volume (VL) of kale pieces was calculated and recorded according to VL (ml)= VC - VR. The shrinkage ratio (SR) of the sample was then calculated from the sample's volume difference before (VL, fresh) and after (VL, dried) drying by IR or hot air as follows:

$$Shrinkage\ degree\ (\%) = \frac{Volume\ of\ fresh\ kale - Volume\ of\ dried\ kale}{Volume\ of\ of\ fresh\ kale}\ x\ 100$$

The shrinkage degree of kale dried by IR and hot air are shown in Figure 10. The shrinkage degree increased with an increase in IR and hot air drying temperatures. IR drying at 70°C had a significantly higher shrinkage degree than all other drying treatments.

**Figure 10: Shrinkage Degree of Kale Dried by IR and Hot Air Drying**




*Source: University of California, Davis*

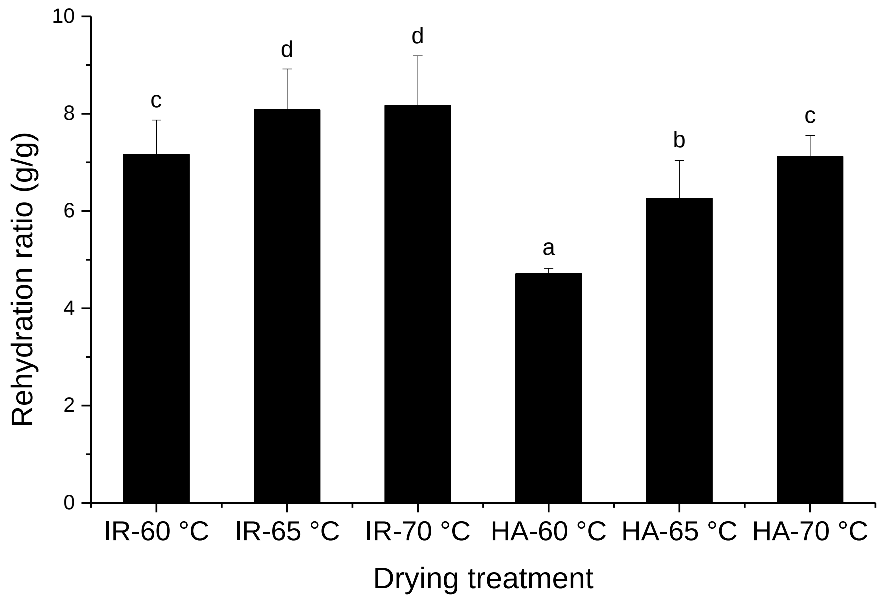
### Rehydration Ratio

The rehydration ability of the dried kale samples was evaluated using the method described by Aghbashlo, Kianmehr & Hassan-Beygi (2010) with some modification. About 2 g of dried kale samples were immersed into 250 ml distilled water at 75°C for 5 minutes. The immersed samples were drained over a mesh for 30 seconds and quickly blotted with paper towels three times gently to eliminate the surface water and then reweighed. The rehydration ratio (RR) of the sample was then calculated from the sample's weight difference before (w) and after ($w_d$) the rehydration as follows:

Rehydration ration RR= $W_d \div W$.

The rehydration ratio of kale is shown in Figure 11. The rehydration ratio of IR dried samples varied from 7.1 to 8.1 g/g, whereas the rehydration ratio of hot air dried kale samples were in the range of 4.6 to 7.0 g/g as shown in Figure 11. The rehydration ratio of kale samples dried with IR at 65°C and 70°C were significantly higher than that of the hot air dried kale samples. The IR dried samples had significantly higher rehydration ratios than did the hot air dried samples at similar hot air temperatures. A higher rehydration ratio shows that the IR dried kale particles are more porous and can regain its original characteristics by absorbing water.

**Figure 11: Rehydration Characteristics of Kale**




*Source: University of California, Davis*

## Total Carotenoids and Vitamin C Contents

The carotenoid content of the dried kale samples was determined from the same extract used for chlorophyll estimation by recording the absorbance at 480 nm. The carotenoid content was calculated by using the method and formula described by (Kirk & Allen, 1965). Vitamin C content was determined as the sum of ascorbic acid (AA) and dehydroascorbic acid (DHAA) using the spectrophotometrical method. Oxalic acid solution (2 g/100 ml) was used for extraction of the AA. After quantitative reduction of 2,6-dichlorophenolindophenol dyestuff by AA, and extraction of the excess dyestuff using xylene, the excess was measured at 500 nm in a Shimadzu UV-160A spectrophotometer and compared with the vitamin C reference standard.

The carotenoid content and vitamin C content of IR dried and hot air dried kale are shown in Table 4. The IR dried kale contained significantly higher carotenoid and vitamin C content than hot air dried samples did.

**Table 4: Carotenoid and Vitamin C Contents of Kale Dried by Infrared and Hot Air at Different Temperatures**

| Drying condition | Carotenoids/ (mg/100g DW) | Vitamin C/ (mg/100g DW) |
|---|---|---|
| IR, 60 °C | 15.96±0.72[cd] | 153.87±12.35[d] |
| IR, 65 °C | 14.17±0.68[c] | 145.16±12.44[d] |
| IR, 70 °C | 12.43±0.61[c] | 120.67±10.61[c] |
| HA, 60 °C | 8.32±0.37[b] | 73.11±6.29[b] |
| HA, 65 °C | 7.84±0.35[b] | 69.98±6.11[b] |
| HA, 70 °C | 6.06±0.31[a] | 54.52±4.97[a] |

*Source: University of California, Davis*

## Conclusions

The results showed that IR drying at product temperatures of 60℃, 65℃ and 70℃ required 70, 60 and 50 minutes, respectively, compared to 5, 4.5 and 4 hours required by HA drying at 60℃, 65℃ and 70℃, respectively. IR drying at 70℃ reduced the drying time by 190 minutes or 79%. The infrared dried kale samples had significantly higher quality attributes in color, carotenoids, and vitamin C contents from significant reduction in drying time. The lab study with kale showed that very thin leafy vegetables could be dry-blanched by IR heating at lower IR intensities than carrot slices and provide more hot air drying time reduction compared to drying of sliced vegetables and fruits.

# CHAPTER 3: Commercial Scale System

## Design and Installation

The project team designed, built and tested a commercial scale SIRDBHAD system with a targeted processing capacity of 70 kg (fresh produce) per hour with an annual capacity of 133,500 kg. The SIRDBHAD system will continuously be operated. The commercial scale SIRDBHAD system was designed and fabricated in collaboration with Treasure8, San Francisco, California and Heat and Control, Hayward, California.

The results from the sequential IR and hot air drying of carrots and kale showed that the IR heating can effectively blanch and partially remove the moisture content. The IR dry-blanched sample had low POD activity, better crispness, color and nutrients, and reduced the drying time compared to hot air drying. With the IR drying temperature and drying time used in the lab study as a basis, the design parameters of the commercial scale dryer were determined.

### Preliminary Data for Design

To determine the IR heating time, hot air-drying time and the hot air velocity required for the design of SIRDBHAD system, an IR heating unit available at Heat and Control (Figure 12) was tested for its suitability for use with fruit and vegetable slices and preliminary design data were collected. A hot air dryer unit of 12” x 6” was designed with a wire screen at the bottom and the hot air was passed from the bottom. IR blanched beet slices were filled to a bed thickness of three inches. Sugar beet slices of 1.2 mm thickness were used in the study. The results showed that IR heating by two passes (each 30 seconds) for 60 seconds total, flipping the slices after the first pass, reduced the moisture content from 87 percent to 60 percent and did not make the slices stick together when stacked in layers for hot air drying. Hot air drying at 85ºC for 60 minutes reduced the moisture content to about 3 percent. This data will be used in the design of SIRDBHAD system. As the IR emitter used in this study had at least two times the IR intensity that the natural gas catalytic IR (CIR) emitters had, the heating time required for CIR emitters to produce similar temperatures and blanching was assumed as 2 minutes in the design.

**Figure 12: Beets IR Blanching and Hot Air**

(a) (b)

**a) IR heating/blanching (left) and b) hot air drying of sweet beet slices(right)**

*Source: University of California, Davis*

## Design of System

The SIRDBHAD system has three segments: (1) CIR dryer unit, (2) an elevating conveyor, (3) HA dryer unit, and (4) ambient air cooler unit and control system. A Grote S/A 400 vegetable slicer/cutter will be added at the front to the system for slicing.

### Infrared Dryer/Dry-Blanching Unit

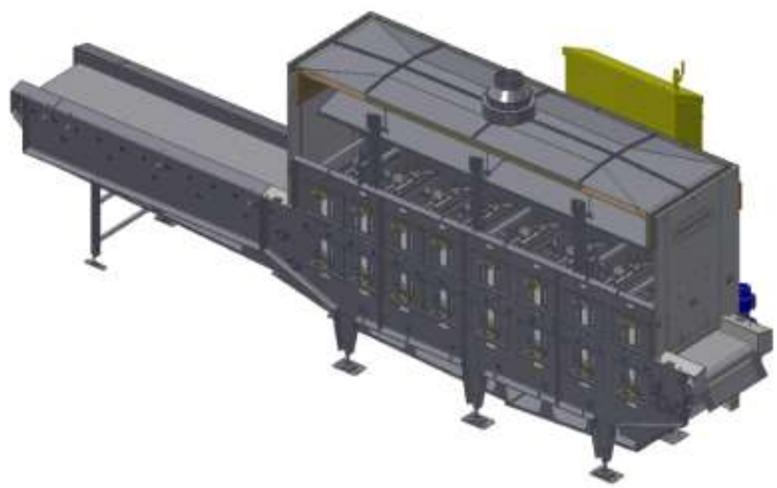
The IR dryer unit is shown in Figure 13. The total length of the IR dryer is 16 feet. IR emitter assemblies are mounted on a one-piece structural frame with manual adjustment to allow the whole burner footprint to adjust up or down +/- 3 to 8 inches. All product and atmosphere contact parts inside the oven and the outside oven surfaces including the supporting structure were constructed of type-304 stainless steel. All piping and fittings are of stainless steel. The oven conveyor is driven by an inverter-rated wash-down duty gear motor.

The conveyor is made up of a 36" wide balanced weave stainless steel belt with 34" usable width. The conveyor rides on staggered stainless steel supports inside the oven. The shafts and bearings are made of stainless steel. Bearings are located on the outside wall of the oven mounted to stand-offs for sanitation. . A stainless steel stationary hood is provided with a support frame for machine-mounting.  The hood has an exhaust port in the center. A tube-axial exhaust fan and variable frequency drive (VFD) controller are used in the installation. Side-mounted insulated heat shields encase the entire heat chamber to prevent heat loss.

The IR emitters are provided with a separate pre-assembled gas train consisting of the burner control devices and valves mounted in a stainless steel gas panel. All components were pre-wired to a junction box. A combustion air blower supplied the air to the IR emitters for complete combustion of natural gas. An IR control system is provided to operate the IR drying unit.

The IR emitters were placed above the conveyor belt. The dryer capacity will be varied from 89-130 kg/hr of fresh produce by operating the dryer with an IR heating time of 3 minutes to 2 minutes, respectively. The IR dryer will dry the product from an initial moisture content of 86-90% to 77-80% depending on the initial moisture content of vegetable/fruit slices used for drying.

**Figure 13: IR Drying Section of the SIRDBHAD System**



*Source: University of California, Davis*

### Elevator Conveyor

An elevator conveyor transfers the IR heated fruits and vegetable slices to the hot air section. The elevator conveyor is 3 feet wide and operated by a gear motor as shown in Figure 14. The conveyor belt is made up of plastic with a rough surface to allow air movement around the slices during passage from the IR dyer to the hot air dryer.

**Figure 14: Elevator Conveyor of the SIRDBHAD System**

*Source: University of California, Davis*

### Multi Pass Hot Air Dryer

The dryer assembly is complete with its own conveyor, circulating fans, gas burner and safety controls. All product and atmosphere contact parts inside the dryer chamber, outside dryer chamber surfaces and the supporting structure are made up of stainless steel. Dryer piping, fittings and valves are T-304 stainless steel. Air intake to the dryer is controlled by means of an automatic damper located on the suction side of the circulating fans. Heating is done by a direct fired package gas burner system. The heated air passes up through the three product conveyors and is returned down a side duct for recirculation.

The dryer casing is a sealed and insulated double walled design. Construction is of T-304 stainless steel with 12 gauge used for the inner walls and 16 gauge for the outer walls. Test ports are located at various locations on the dryer casing with screw caps to allow for desired operational testing. The main conveyor belt system is a stainless steel, chain edge woven wire belt using a steel roller chain attached to stainless steel cross rods. Package type natural gas fired burners are provided and fire into the air return ducts. The package gas burner system has a self-contained blower, air filter, spark ignition, and ultraviolet flame detector. The three pass dryer can be operated to have different residence times in each pass and the air flow through different passes can be varied.

### Ambient Air Cooler Unit

A stainless steel ambient air cooler includes a high temperature belt, washable stainless steel air filter, and access doors as shown in Figure 15. The conveyor belt system is a stainless steel, chain edge woven wire belt utilizing a steel roller chain attached to stainless steel cross rods. An inverter rated wash-down duty gear motor is provided for conveyor drive. A steel exhaust fan with VFD is provided. The cooler will cool the product with the ambient air.

**Figure 15: Ambient Air Cooler**

*Source: University of California, Davis*

## Installation of System

Fabricating the different parts of the dryer were carried out by Heat and Control, Hayward, California and were transported and installed at Treasure8's testing facility in Richmond, California. The different sections of the SIRDBHAD system unit are shown in Figures 16-20. The different parts were transported to Treasure8's drying facility in Richmond, California and installed together. The SIRDBHAD system after installation at Richmond, California is shown in Figure 21.

**Figure 16: Front View of Infrared Heating Section of System with Conveyor for Feeding Fresh Vegetable and Fruit Slices**

*Source: University of California, Davis*

**Figure 17: Rear Side of the Infrared Heating Section and the Elevator for Feeding to Hot Air Drying Section**

*Source: University of California, Davis*

**Figure 18: Hot Air Drying Section of System**

**Photo shows the elevator for feeding IR dried slices to hot air drying section.**

*Source: University of California, Davis*

**Figure 19: View of the Assembled System**

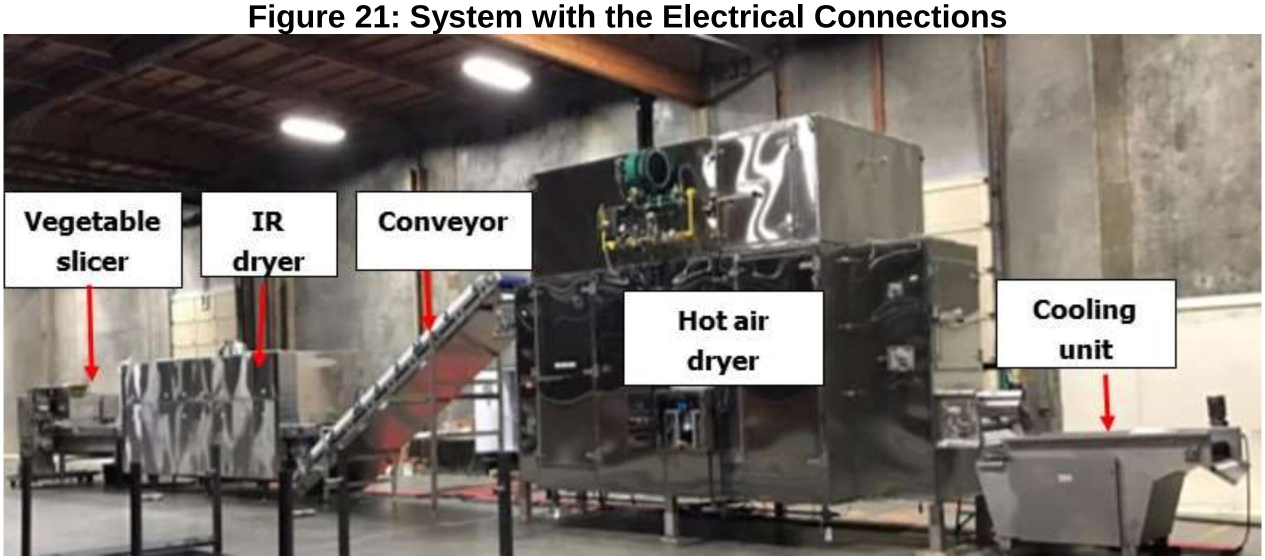

**Photo shows the IR drying, hot air drying and ambient air cooling sections.**

*Source: University of California, Davis*

**Figure 20: Main Electrical Control Box with Relays and Control Units of System**

*Source: University of California, Davis*

**Figure 21: System with the Electrical Connections**




*Source: University of California, Davis*

## Drying Tests with System

After the SIRDBHAD system was installed at Treasure8's testing facility, researchers from UC Davis, Treasure8, and the United States Department of Agriculture (USDA) worked on operating the individual units, including the IR drying unit, hot air dryer unit and ambient air cooler, at the design settings. Preliminary trials were conducted with small samples of apple slices (Figure 22) and the proper operation of different sections of the SIRDBHAD drier was established. The product temperatures and moisture loss after IR heating and hot air drying were determined. The preliminary tests showed that the dryer blanched and dried of the slices to the required moisture content.

**Figure 22: Apple Slices Entering and Leaving the IR Dryer**

*Source: University of California, Davis*

### Dryer Operation

The Grote commercial vegetable slicer was placed in front of the IR dryer and its cutting head adjusted to produce slices of different thicknesses depending on the product. The commercial slicer was used to slice apples and sweet potatoes. Other vegetables were sliced in a meat slicer to produce slices of required thickness that were spread across the conveyor uniformly. The thickness of the slices was measured using a caliper. The thickness was measured at five locations of each slice and the average was obtained. The average thicknesses of five slices were measured and the average value was reported as the slice thickness. The moisture content of the fresh and dried slices was measured by drying about 10 g of product at 105°C for 24 hours in a hot air oven. The IR drying time varied between 2 to 3 minutes depending on the type of product to be dried/dry-blanched. The temperature after IR heating was measured using an infrared thermometer for five slices and the average value was reported. The weight of vegetable slices per unit area was determined by spreading the slices in a single layer and weighing the slices in an electronic balance. The total weight of slices in the infrared dryer was calculated from the weight per unit area multiplied by the total conveyor belt area inside the IR dryer (6528 square inches).

## Energy Consumption

### IR drying unit

Natural gas consumption was calculated from the natural gas pressure entering the IR emitter sections. The two IR sections were operated at the required pressures during the drying process. The electricity consumption by the motor operating the conveyor belt was determined from the current used by the motor.

### Elevator conveyor

The electricity consumption by the motor operating the conveyor was determined from the current used by the motor.

### Hot air dryer

The natural gas consumption to heat the air was calculated from the natural gas pressure entering the IR emitter sections. The electricity consumption by the motor operating the three conveyor belts and air recirculation units was determined from the current used by the motor.

### Ambient air cooler

The electricity consumption by the motor operating the conveyor and the air blower was determined from the current used by the motor.

## Results of System Experiments

### Drying Conditions of Fruits and Vegetable Snacks

The initial thicknesses of the kale, carrot, pear, squash, bell pepper and apple slices were measured before feeding into the IR heating section and the values are shown in Table 5. The natural gas pressures entering the first two sections of the IR drying section, the IR drying times, the sample temperatures after IR heating and the hot air drying times are also shown.

**Table 5: Size, Pressure Settings, and Drying Times for Different Fruit and Vegetable Slices**

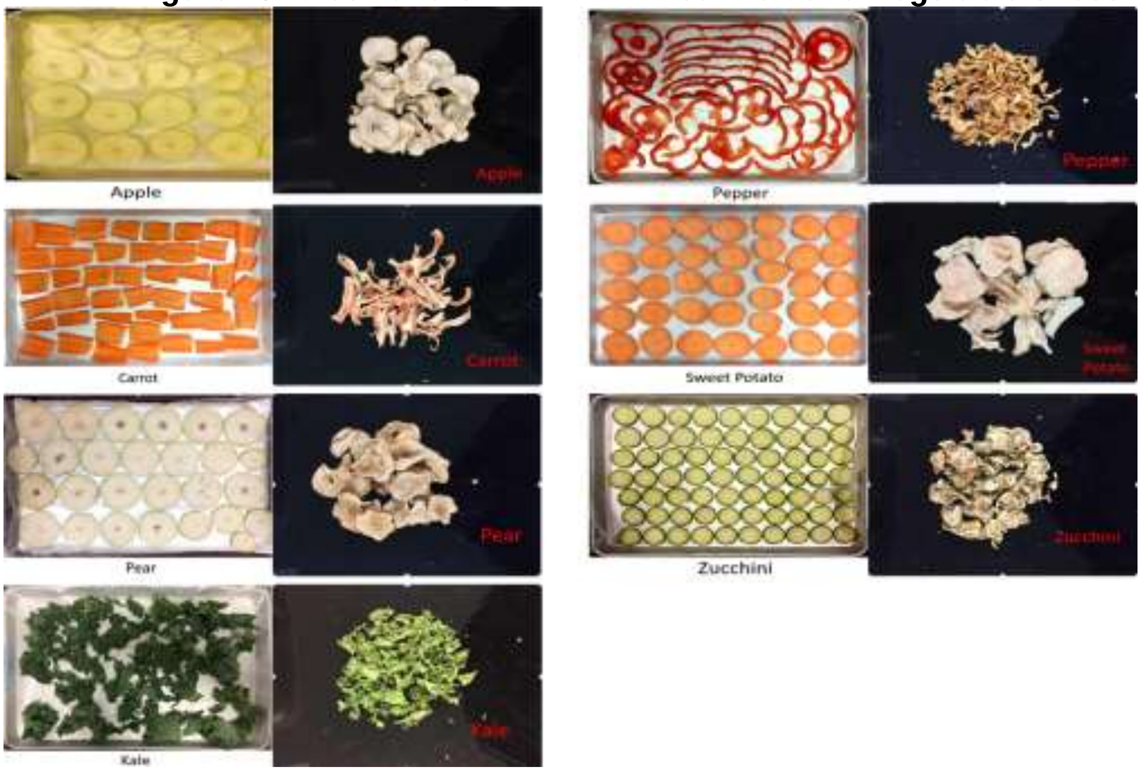
| Product | Thickness, mm | IR emitter gas pressure (Inches of Water Column) Zone 1 | IR emitter gas pressure (Inches of Water Column) Zone 2 | IR drying time, min | Temp. after IR drying, °C | Hot air drying time, min |
|---|---|---|---|---|---|---|
| Kale | 1.27 ±0 .05 | 6.4 | 3.2 | 2 | 75.0 | 50 |
| Carrot | 1.41± 0.04 | 6.4 | 6.4 | 2.5 | 94.0 | 60 |
| Pear | 1.75 ± 0.16 | 6.4 | 6.4 | 2.25 | 93.0 | 60 |
| Zucchini | 2.21 ±0 .03 | 6.4 | 6.4 | 2.25 | 85.0 | 60 |
| Bell pepper | 3.39± 0.04 | 6.4 | 6.4 | 2.25 | 81.3 | 60 |
| Apple | 2.03 ± 0.16 | 6.4 | 6.4 | 2.5 | 81.7 | 60 |
| Sweet potato | 1.61± 0.04 | 6.4 | 6.4 | 2.5 | 82.5 | 60 |

*Source: University of California, Davis*

## Moisture Content

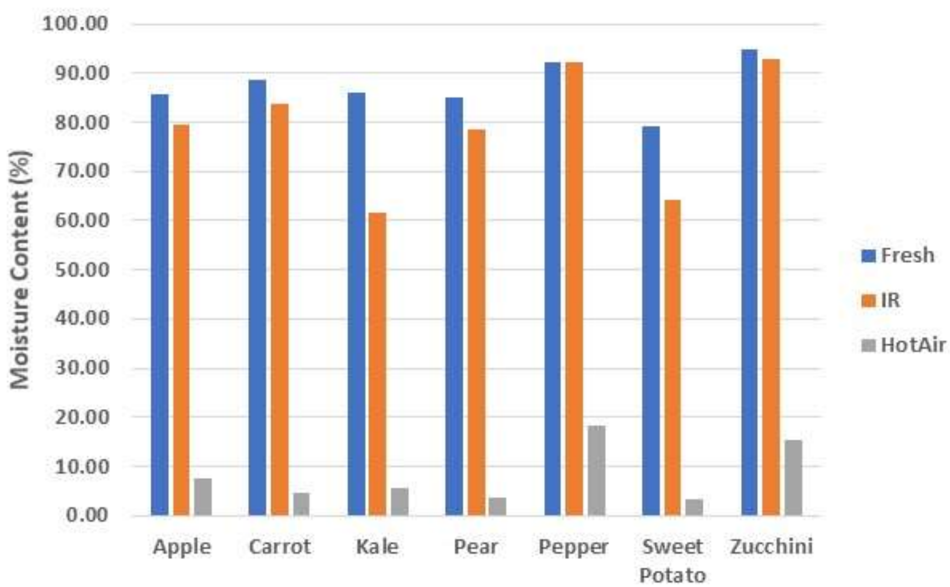
The fresh and SIRDBHAD dried samples of fruits and vegetable slices are shown in Figure 23. The initial moisture contents (MC) of the fruit and vegetable slices and moisture contents after IR drying and hot air drying are presented in Figure 24. The initial moisture content varied from 94.79% (zucchini) to 79.15% (sweet potato). The moisture loss by IR drying varied from 24.31% (kale) to 1.73% (zucchini) depending on the initial MC and the structure of the vegetable and fruit slices. The final MC after hot air drying ranged from 3.56% (pear) to 18.25% (pepper). The slices with high moisture content were dried in the hot air batch dryer to bring the moisture content to less than 5% and then quality evaluation was performed. The time taken in the batch dryer was added to the energy calculation.

**Figure 23: Fresh and SIRDBHAD Dried Fruit and Vegetable Slices**




*Source: University of California, Davis*

**Figure 24: Moisture Content of Fresh, After Infrared and Hot Air-Dried Fruit and Vegetable Slices**




*Source: University of California, Davis*

**Thickness of Dried Products**

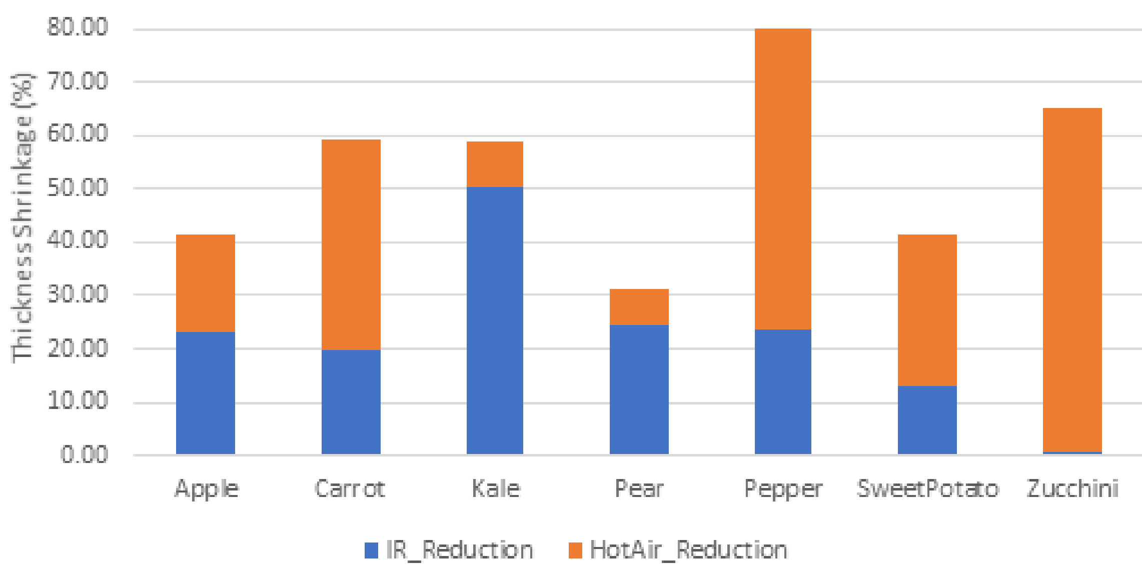
The thicknesses of fresh fruit and vegetable slices, thicknesses after IR drying and thicknesses after SIRDBHAD are shown in Table 6. The thickness of the fresh samples varied from 1.27 mm (kale) to 3.29 mm (pepper). The thickness shrinkages of different fruit and vegetable samples during IR drying and hot air drying are shown in Figure 25. Shrinkage in thickness due to IR drying alone ranged from 0.75% (zucchini) to 50.53% (kale) and the total shrinkage after SIRDBHAD varied from 31.05% for pears to 80.04% for peppers.

**Table 6: Thickness of Fresh, IR Dried and Hot Air Dried Fruit and Vegetable Slices**

| Category | Thickness of fresh slices, mm | Thickness after IR drying, mm | Thickness after Hot Air drying, mm |
|---|---|---|---|
| Apple | 2.03±0.08 | 1.56±0.09 | 1.19±0.01 |
| Carrot | 1.41±0.03 | 1.13±0.06 | 0.57±0.05 |
| Kale | 1.27±0.03 | 0.63±0.05 | 0.52±0.02 |
| Pear | 1.75±0.08 | 1.32±0.08 | 1.21±0.08 |
| Pepper | 3.29±0.03 | 2.52±0.08 | 0.66±0.05 |
| Sweet Potato | 1.61±0.02 | 1.4±0.02 | 0.94±0.01 |
| Zucchini | 2.21±0.02 | 2.2±0.09 | 0.77±0.03 |

*Source: University of California, Davis*

**Figure 25: Thickness Shrinkage of Fruit and Vegetable Slices During SIRDBAHD Drying**



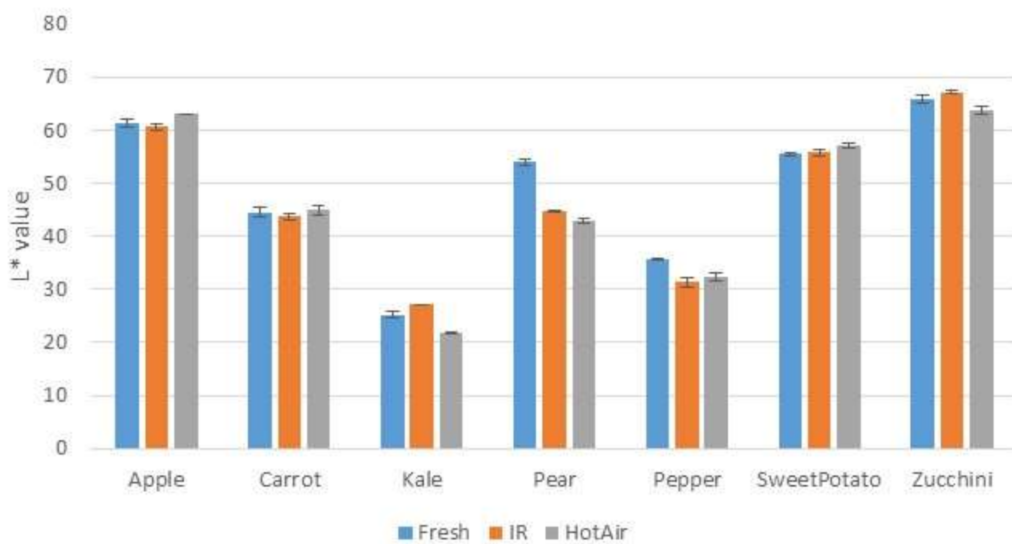

*Source: University of California, Davis*

## Color

The color of the fresh slices and their color after IR drying and hot air drying were measured using the colorimeter. The L, a and b values are shown in Figures 26, 27 and 28, respectively. The L value represents the darkness to lightness gradation, the a value represents the greenness to redness values and the b value represents the blueness to yellowness values.

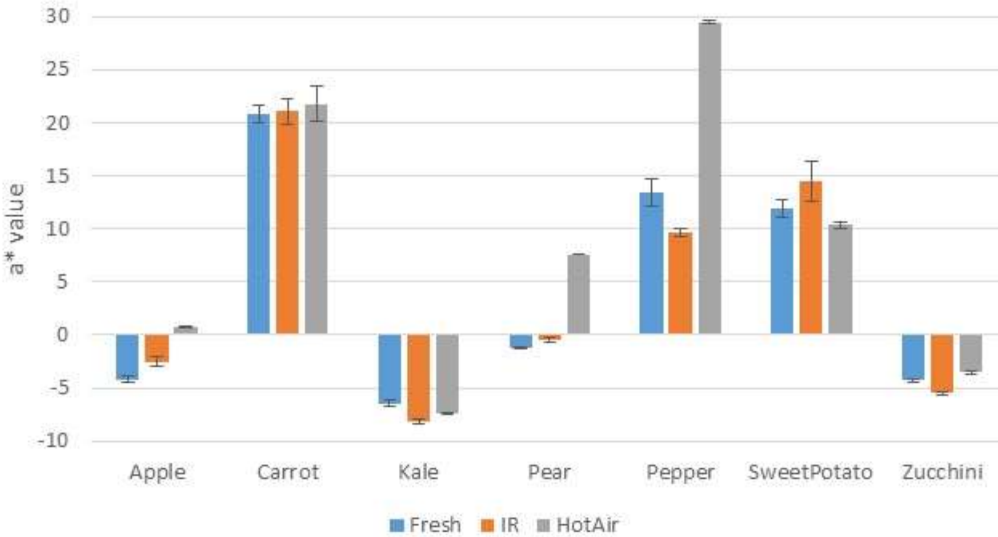
The L value of the fresh slices ranged from 25.24 (kale) to 65.92 (zucchini). After IR drying, the L value decreased for all the samples except for kale and zucchini, which showed a slight increase as seen in Figure 26. After hot air drying, the L* values of apples, carrots and sweet potatoes were higher than the L* values of the corresponding fresh slices, which showed that these products turned slightly darker after SIRDBHAD.

**Figure 26: Lightness (L*) Values of Fresh, After IR Dried and After Hot Air Dried Fruit and Vegetable Slices**




*Source: University of California, Davis*

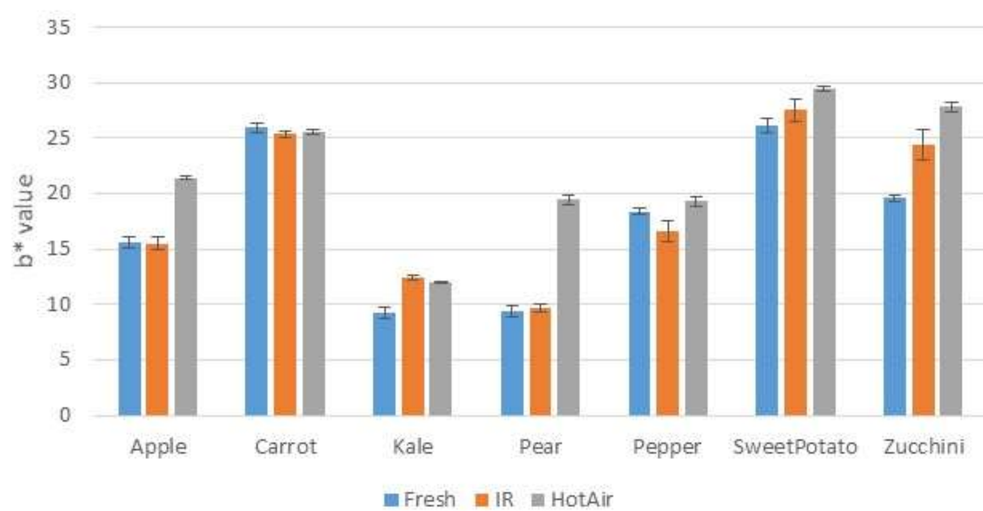
**Figure 27: Greenness (a*) Values of Fresh, After IR Dried and After Hot Air Dried Fruit and Vegetable Slices**




*Source: University of California, Davis*

A negative a value indicates greenness and positive a value shows redness. The a values of apple, carrot, pear, pepper and zucchini slices increased during the SIRDBHAD, as shown in Figure 27, whereas the a values of kale and sweet potatoes decreased. The increase in a values showed that the slices are turning from green to red. Apples had negative a value before hot air drying, meaning that slight browning occurred during the hot air drying process. Pears had a strong PPO enzyme value, which was due to the fast browning reaction that occurred before the IR blanching.

**Figure 28: Yellowness (b*) Values of Fresh, After IR Dried and After Hot Air Dried Fruit and Vegetable Slices**




*Source: University of California, Davis*

The positive b values in Figure 28 show that the samples are yellow. The yellowness or b values of all the vegetable and fruit slices increased significantly during SIRDBHAD as the samples turned from blue to yellow due to the browning reaction caused mostly by non-enzymatic browning, as enzymatic browning had been eliminated by IR drying/dry blanching.

The L, a and b values showed that, during SIRDBHAD, samples are browning. As most PPO and PO enzymes are inactivated by IR dry blanching, non-enzymatic browning is the major reason for the browning reaction.

**Crispness**

For fruit and vegetable chips, a crispy texture is always expected because crispness is related to freshness and high quality. A recommended assay to study the texture of fried and dried carrots is the puncture test, which measures the initial slope and the maximum force at the breaking point from the force curves (Pedreschi & Moyano, 2005; Shyu, Hau & Hwang, 2005). A puncture test was performed on the dried carrot slices using a TA-XT2i Texture Analyzer (Stable Micro Systems Ltd., Vienna Court, Surrey, UK) to measure the textural properties of dried slices. The initial slope is positively correlated with crispness, while an increase in the maximum force indicates less crispness. The initial slope and the maximum force values of the fruits and vegetables slices are shown in Table 7. The tables show higher initial slope values and a lower maximum force for all the samples, indicating that SIRDBHAD processed chips are crispy.

**Total Phenolic Content**

The antioxidants in the extracts were determined using the total phenolics in terms of tannic acid equivalents, according to a modified Folin–Ciocalteu method (Li et al., 2006). Folin–Ciocalteu reagent, tannic acid, and 2,2-diphenyl-1-picrylhydrazyl (DPPH) were purchased from Sigma–Aldrich Company (St. Louis, MO, USA). Methanol and sodium carbonate (Na2CO3) were obtained from Fisher Scientific Inc. (Pittsburgh, PA, USA).

**Table 7: Crispness of SIRDBHAD Dried Slices**

| Product | Initial Slope, kg/sec | Maximum force, kg |
|---|---|---|
| Apple | 1.13±0.32 | 0.25±0.04 |
| Carrot | 3.13±0.51 | 0.51±0.04 |
| Kale | 0.09±0.05 | 0.04±0.01 |
| Pear | 0.84±0.20 | 0.30±0.06 |
| Pepper | 0.99±0.24 | 0.38±0.09 |
| Sweet potato | 2.80±0.59 | 0.45±0.11 |
| Zucchini | 0.41±0.20 | 0.13±0.04 |

*Source: University of California, Davis*

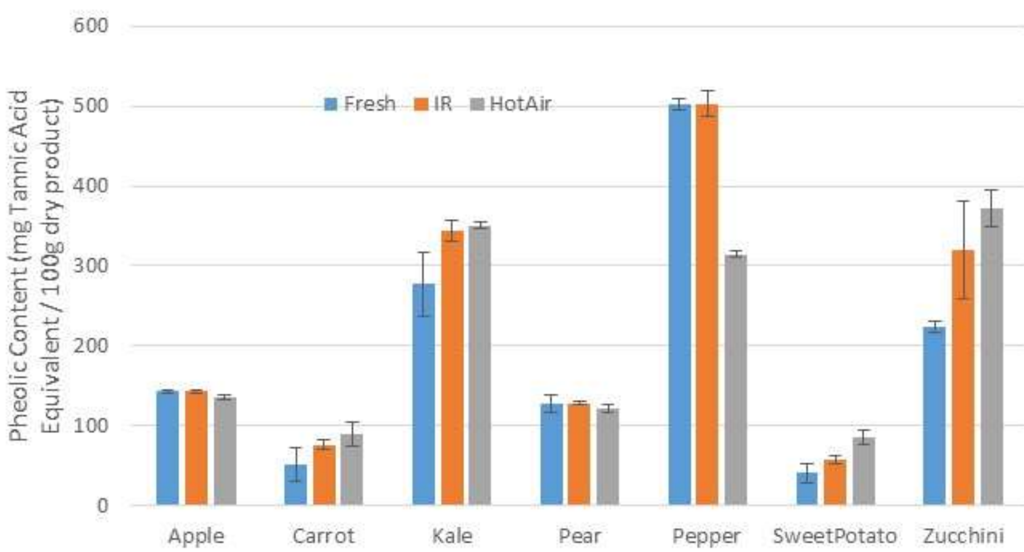
An extract sample of 60 μL was thoroughly mixed with 2 mL of $Na_2CO_3$ (7.5%) and 2.5 mL of 10-fold diluted Folin–Ciocalteu reagent using a vortex mixer (K-550-G Vortex-Genie, Scientific Industries Inc., Bohemia, NY, USA). The mixed solution was held in a water bath for 30 min at 25°C and then its absorbance was measured at 760 nm using a UV-Vis-NIR spectrophotometer (UV-3600, Shimadzu, Japan). Three measurements were conducted for each liquid sample and the test was replicated three times. The blank was prepared using the above procedure, but the extract was replaced by the same volume of de-ionized (DI) water. The total phenolic yield % was calculated using following equation:

$$\text{Total phenolic yield} = \frac{\text{CtVt}}{100\text{W}} * 100\%$$

Where $V_t$ is the total volume of liquid extract (L) at a given extraction time t and W is the dry weight of sample (g).

Total phenolic contents extracted from the fresh, IR dried and hot air dried fruit and vegetable slices are shown in Figure 29. The phenolic content of fresh samples varied from a minimum value of 40.56 (mg Tannic Acid Equivalent 100g dry product) for sweet potato to a maximum value of 501.97 (mg Tannic Acid Equivalent /100g dry product). The IR and hot air drying caused the decrease in the phenolic contents of apple, pear and pepper and increased the phenolic contents of carrot, kale, sweet potato and zucchini. It was reported by several researchers that IR and hot air heating causes an increase or decrease in the phenolic content depending on the enzymes, temperature, heating time and heating rate, which need to further investigation.

**Figure 29: Total Phenolic Content of Fresh, After IR Dried and After Hot Air Dried Fruit and Vegetable Slices**



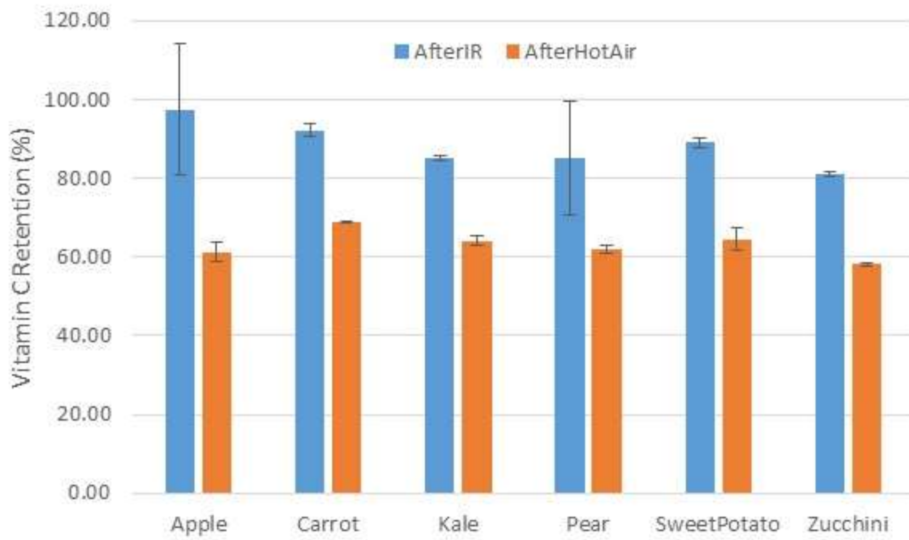

*Source: University of California, Davis*

## Vitamin C

Vitamin C (ascorbic acid) is the most heat labile among all the vitamins, and the extent of vitamin C loss during thermal processing is influenced by temperature, presence of oxygen, and drying time. Vitamin C content of the carrot slices was determined by titration of filtrate against 2,6-dichlorophenolindophenol and expressed on dry weight basis. Fresh carrots were used as the control. Vitamin C retentions after IR drying and hot air drying for different snacks are shown in Figure 30.

From Figure 30, it can be seen that vitamin C retention after IR drying ranged from 81.1% for zucchini to 97.48% for apple slices. The vitamin C retention after hot air drying ranged from 58.11% for zucchini to 68.90% for carrot slices. More vitamin C was lost by hot air drying compared to IR drying as the hot drying was performed for a longer time than IR drying.

**Figure 30: Vitamin C Retention After Infrared and Hot Air Drying of Fruits and Vegetable Slices**

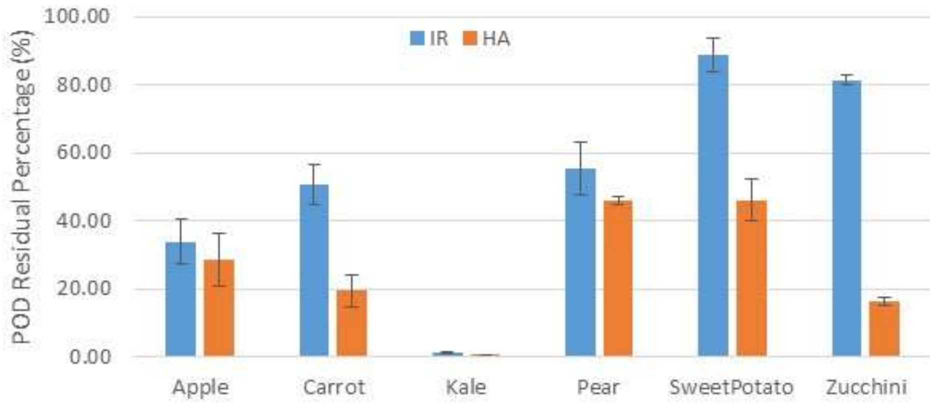



*Source: University of California, Davis*

## Inactivation of POD Enzyme

The residual activity of peroxidase (POD) enzyme after IR drying and hot air drying is shown in Figure 31. The IR drying inactivated about 99% of POD enzyme in kale and only 11% in sweet potato. The POD enzyme activities of fruits such as apples and pears were inactivated by IR drying. About 5-10% of the remaining enzymes in the apples and pears were inactivated by hot air drying.

**Figure 31: Residual POD Activity of Fruit and Vegetable Slices After Infrared and Hot Air Drying**




*Source: University of California, Davis*

POD is one of the most heat resistant enzymes present in many fruits and vegetables, making it a common enzymatic indicator for blanching (Güneş & Bayindirli, 1993; Sheu & Chen, 1991). When POD is inactivated, most of the other enzymes in fruits and vegetables might not survive (Halpin & Lee, 1987). It was reported that pulsed electric field pretreatment can only reduce 30–50 percent of the POD activity. In the treatments, SIRDBHAD achieved more than 50 percent POD inactivation for all the products and as high as 99 percent inactivation for kale.

## Quality of SIRDBHAD Dried and Freeze Dried Snacks

To compare the quality of SIRDBHAD dried chips with that of freeze dried chips, the fruit and vegetable slices were freeze dried using the lab scale freeze drier and the quality of the freeze dried chips were determined. For conducting the freeze drying, the fruit and vegetable slices were first frozen in a freezer at -30°C and then freeze dried. The frozen slices were freeze dried using the Labconco stoppering tray dryer (catalog #7948020) using the following program for about 70 hours:

- Step1: -20°C, 10 hours
- Step2: -10°C, 12 hours
- Step3: +5°C, 14 hours
- Step4: +10°C, 16 hours
- Step5: +20°C, 18 hours

The freeze dried slices were used for quality analysis and compared with that of the SIRDBHAD dried chips.

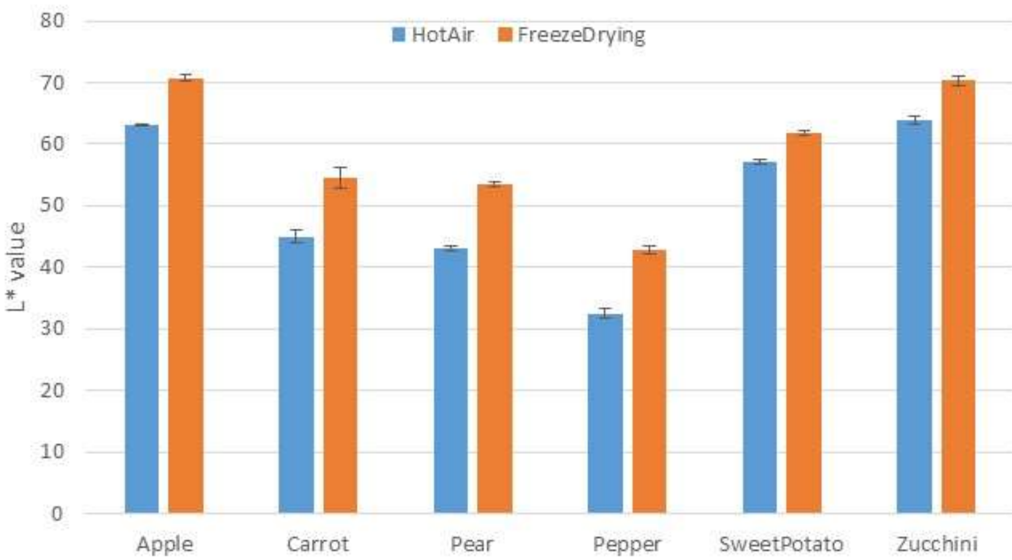
### Color

The color values (L, a, and b) of SIRDBHAD and freeze dried samples are shown in Figures 32 to 34. The lightness values of SIRDBHAD and freeze dried samples showed that the lightness of freeze dried samples were significantly higher than that of the SIRDBHAD dried samples (Figure 35). The lightness of SIRDBHAD dried samples were slightly lower than freeze dried samples which did not affect the overall appearance and acceptability of the products.

The a values of SIRDBHAD and freeze dried samples in Figure 33 showed that freeze drying resulted in more greenness in apples, pears and zucchinis. SIRDBHAD contributed to the greater redness in carrots and pears due to browning.

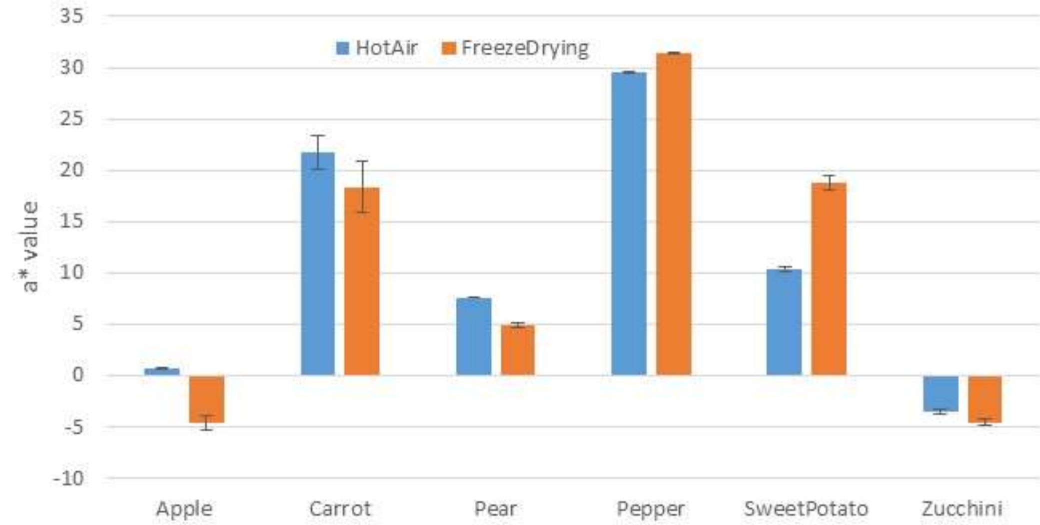
The b values of SIRDBHAD and freeze dried samples in Figure 34 showed that freeze drying resulted in more yellowness of carrots, pears and peppers. SIRDBHAD contributed to the better yellowness of apple, sweet potato and zucchini samples. Overall, comparison of the color parameters showed that the freeze dried samples had lighter color due to the absence of browning compared to SIRDBHAD.

**Figure 32: Lightness (L) Values of SIRDBHAD and Freeze Dried Fruit and Vegetable Slices**



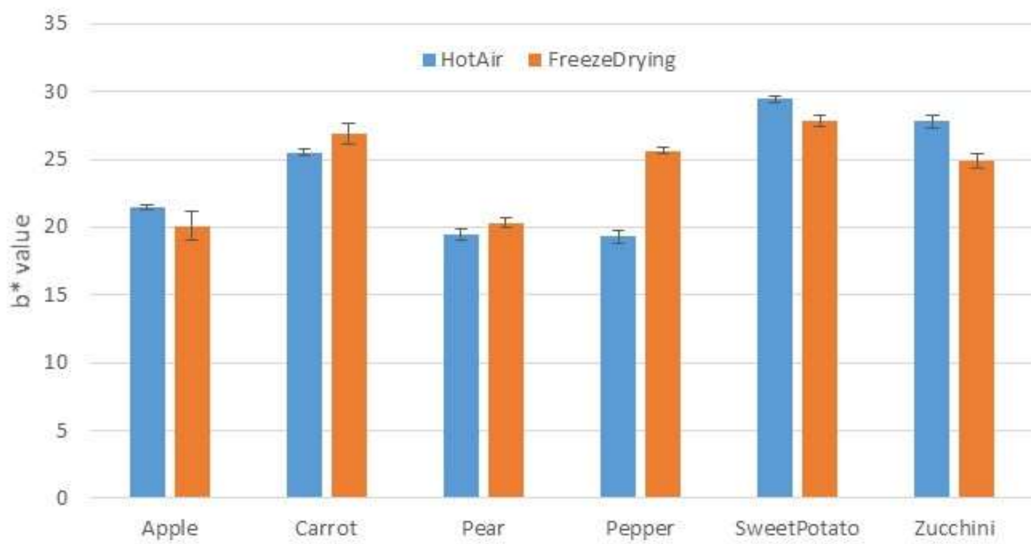

*Source: University of California, Davis*

**Figure 33: Greenness (a) Values of SIRDBHAD and Freeze Dried Fruit and Vegetable Slices**




*Source: University of California, Davis*

**Figure 34: Yellowness (b) Values of SIRDBHAD and Freeze Dried Fruit and Vegetable Slices**

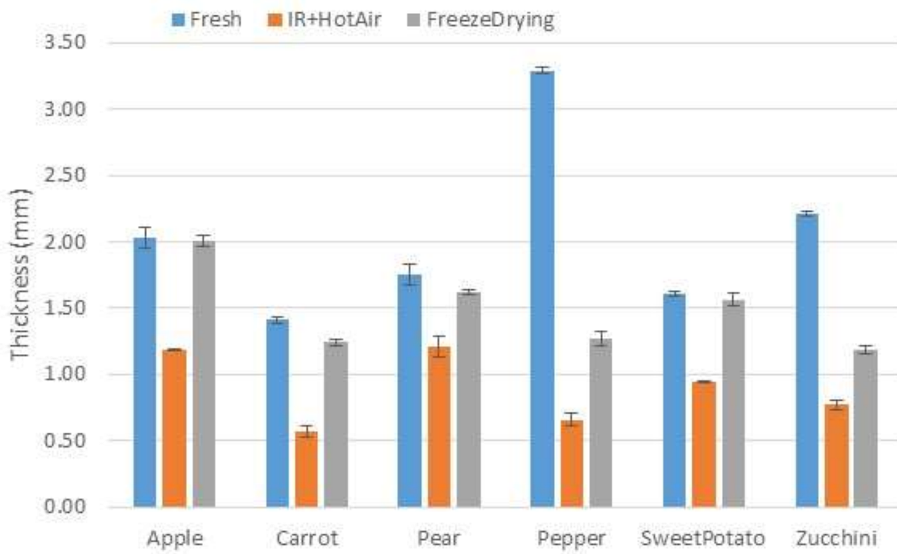



*Source: University of California, Davis*

## Thickness Shrinkage

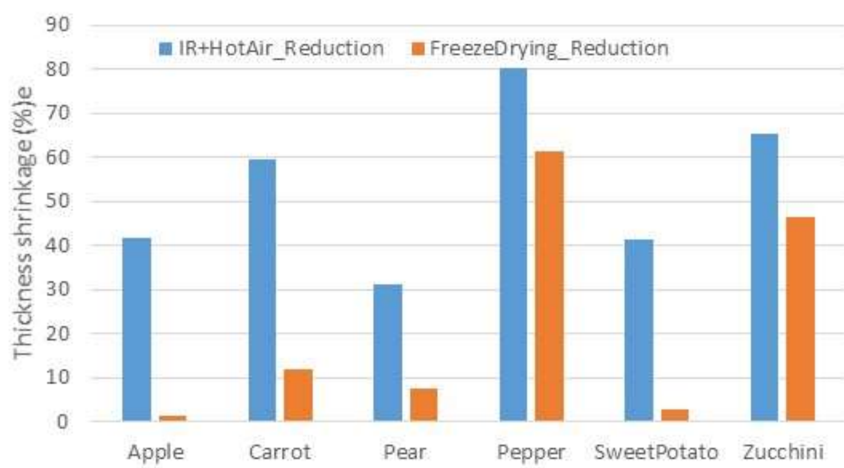
The thickness of the fresh fruits and vegetables slices and the thickness after SIRDBHAD and freeze drying are shown in Figure 35, and the thickness shrinkage in percentage of fresh thickness by SIRDBHAD and IR drying are shown in Figure 36.

**Figure 35: Thickness of Fresh, SIRDBHAD Dried and Freeze Dried Fruit and Vegetable Slices**




*Source: University of California, Davis*

**Figure 36: Thickness Shrinkage of SIRDBHAD Dried and Freeze Dried Fruit and Vegetable Slices**




*Source: University of California, Davis*

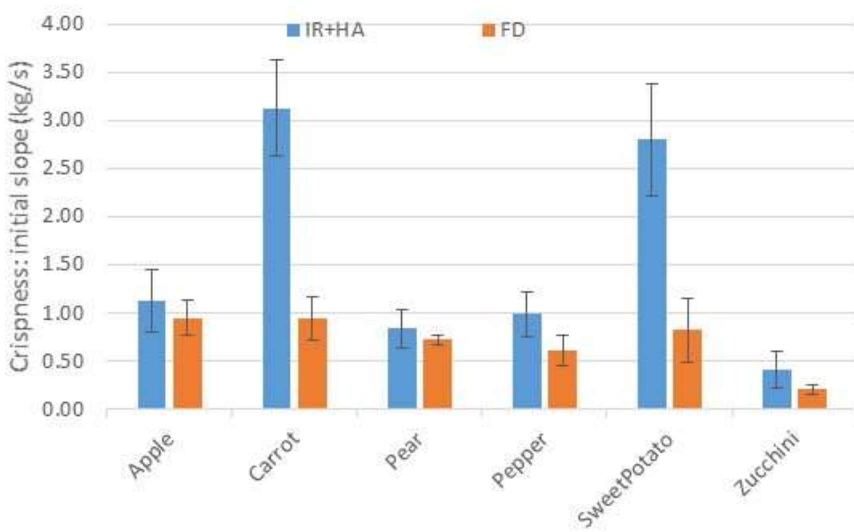
Figures 35 and 36 showed that the SIRDBHAD dried slices are much thinner than the freeze dried slices as expected since freeze drying retains the structure and texture than SIRDBHAD technology. The thickness shrinkage during freeze drying (Figure 36) was significantly lower than the shrinkage during SIRDBHAD.

**Crispness**

The initial slope and maximum force values for the SIRDBHAD dried and freeze dried fruit and vegetable chips are shown in Figure 37.

All the SIRDBHAD dried slices had a higher initial slope. SIRDBHAD dried carrots, peppers and sweet potatoes had significantly higher initial slopes than those of the freeze dried chips. The initial slope is positively correlated with crispness. So, higher initial slope indicated that the chips are crispier. The SIRDBHAD dried ships had higher initial slope, indicating that they are crispier than the freeze dried chips. Another reason for the better crispness of the SIRDBHAD samples might be that they are thinner than the freeze dried samples, as shown in Figure 37.

**Figure 37: Crispness of SIRDBHAD Dried and Freeze Dried Fruit and Vegetable Slices**

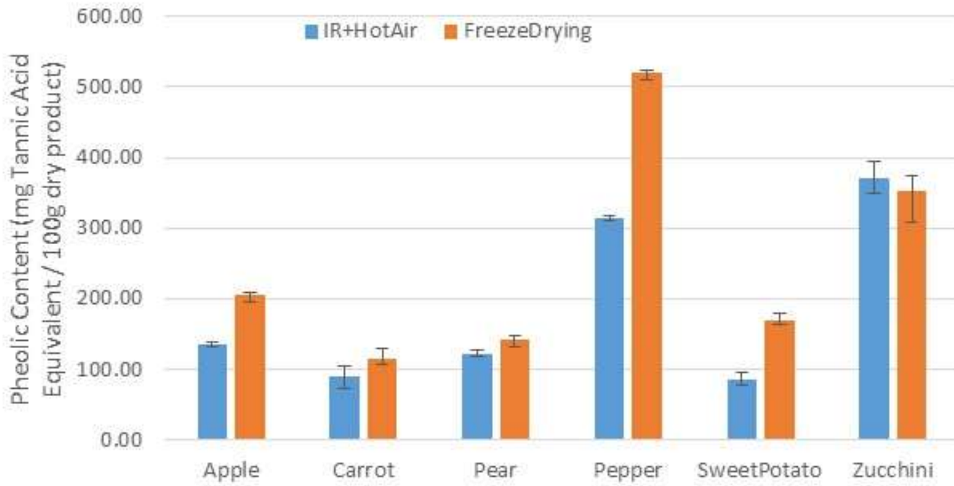



*Source: University of California, Davis*

**Phenolic Content**

Antioxidant activity, measured by the total phenolic content, of SIRDBHAD and freeze dried chips are shown in Figure 38. The total phenolic contents of freeze dried vegetable and fruit slices are higher than those of SIRDBHAD slices. The higher phenolic content in the freeze dried samples is expected as the phenolic content of food products is affected by the increase in temperature and heating time.

**Figure 38: Total Phenolic Content of SIRDBHAD Dried and Freeze Dried Fruit and Vegetable Slices**




*Source: University of California, Davis*

## Sensory Evaluation

The SIRDBHAD dried and freeze dried chip samples of apple, carrot, pear, pepper, sweet potato and zucchini were provided to 10 randomly chosen graduate students of UC Davis for tasting and sensory evaluation. A 9-point hedonic scale was used to evaluate the liking or disliking of quality parameters including appearance, texture, flavor and taste. From the response, the overall acceptance of the chip samples was calculated as the mean value of the four quality parameters. The results of the sensory evaluation test are shown in Table 8.

Table 8 shows that the SIRDBHAD dried products had low flavor compared to freeze dried products. This might be due to the loss of flavor during drying at high temperature. The overall acceptance of the SIRDBHAD dried products were on par with that of the freeze dried products.

**Table 8: Sensory Evaluation Results of SIRDBHAD and Infrared Dried Fruits and Vegetable Snacks**

| Product | Appearance SIRD-BHAD | Appearance Freeze dried | Texture SIRD-BHAD | Texture Freeze dried | Flavor SIRD-BHAD | Flavor Freeze dried | Taste SIRD-BHAD | Taste Freeze dried | Overall Acceptance SIRD-BHAD | Overall Acceptance Freeze dried |
|---|---|---|---|---|---|---|---|---|---|---|
| Apple | 6.7 | 7.8 | 7.4 | 7.6 | 7.9 | 8.3 | 8.1 | 6.8 | 7.53 | 7.63 |
| Carrot | 8.6 | 8.7 | 7.2 | 7.1 | 6.2 | 6.7 | 8.3 | 8.7 | 7.58 | 7.80 |
| Pear | 4.6 | 5.7 | 7.1 | 7.6 | 4.2 | 5.6 | 6.7 | 6.3 | 5.65 | 6.30 |
| Pepper | 7.1 | 7.3 | 6.3 | 6.2 | 5.0 | 5.3 | 5.1 | 4.8 | 5.88 | 5.90 |
| Sweet potato | 6.7 | 7.1 | 7.8 | 7.5 | 6.2 | 6.6 | 7.0 | 6.8 | 6.93 | 7.00 |
| Zucchini | 5.8 | 6.8 | 7.5 | 7.1 | 6.8 | 7.3 | 6.1 | 6.4 | 6.55 | 6.90 |

*Source: University of California, Davis*

## Energy Consumption of System

The natural gas consumption and electricity consumption of the IR drying unit and hot air drying unit were determined from the average gas consumption values per hour. The electrical energy consumed by the elevating conveyor and ambient air cooler was added. The energy consumption of the slicer was determined, and it was assumed that the energy consumption is similar for all the fruit and vegetable slices tested. The energy consumption used to process 100 kg of different products was determined and shown in Table 9. Consumption ranged from 228.17 kilowatts-hours (kWh) to 614.09 kWh to dry 100 kg of fresh produce.

From Table 9 it can be seen that kale had the lowest total energy consumption, followed by sweet potato. Kale is very thin and most of its moisture was been removed during IR drying itself. The sweet potatoes had very low moisture content, which reduced the energy consumption. Bell pepper samples had the highest energy usage followed by zucchini. The energy consumption reported by Wu et al. (2010) for fried potato chips was 833.33 kWh per 100 kg of potato chips. Comparing this frying, SIRDBHAD saved about 26.3 percent (bell pepper) to 72.6 percent (kale). When comparing the potato chips with sweet potato chips, the energy saved by SIRDBHAD is 65.4 percent compare to the frying process.

**Table 9: Energy Consumption of SIRDBHAD System**
**Energy Used per 100 kg of Fresh Product**

| Product | Natural gas, therms | Electricity, kWh | Total energy, kWh | Specific energy, MJ/kg of water removed |
|---|---|---|---|---|
| Apple | 12.57 | 25.89 | 394.21 | 16.73 |
| Carrot | 10.66 | 20.95 | 333.54 | 13.63 |
| Kale | 7.25 | 15.66 | 228.17 | 9.64 |
| Pear | 7.54 | 14.82 | 235.88 | 10.07 |
| Pepper | 22.64 | 50.36 | 614.09 | 24.03 |
| Sweet Potato | 9.22 | 18.11 | 288.32 | 13.30 |
| Zucchini | 16.35 | 35.96 | 515.23 | 19.62 |

*Source: University of California, Davis*

The specific energy consumption of SIRDBHAD system ranged from 9.64-24.03 mega joules per kilogram (MJ/kg) of water removed (Table 9). This is how much energy is required to remove a kilogram of water from the specific product. The specific energy consumption for freeze drying was reported as more than 60 MJ/kg of water removed (Rudy, 2009). Comparing the freeze drying, the SIRDBHAD could save 62.5-82.5 percent of energy used depending on the type of product processed.

# Conclusions

The drying tests with the commercial scale SIRDBHAD system showed that the system had a capacity to dry 78.5 kilograms per hour (kg/ h) to 132.3 kg/h of fresh slices into high quality crispy and healthy chips with attractive color, taste and retains most of the nutrients. The IR dry-blanching inactivated 50-99% of the POD enzyme and significantly reduced the enzymatic browning. Crispness test with the textural analyzer confirmed that the chips produced by SIRDBHAD technology were crispy. The energy required to dry 100 kg of produce with SIRDBHAD system ranged from 228.17 kwh to 614.09 kwh and the specific energy consumption was 9.64 to 24.03 MJ/kg of water removed. SIRDBHAD dried chips are crispier and crunchy with same level of overall acceptance compared to freeze dried products and as that of freeze dried products. The energy saving by SIRDBHAD technology varied from 26.3 percent to 72.6 percent compared to the traditional oil frying. Compared to freeze drying, the SIRDBHAD resulted in huge energy savings in the range of between 62.5-82.5 percent.

# CHAPTER 4: Demonstration and Dissemination of SIRDBHAD Technology

This on-site demonstration tests helps promote adoption of new energy efficient SIRDBHAD technology to produce healthy fruit and vegetable snacks. Participants were shown the significant reduction in consumption of natural gas and electricity; improved product quality and healthfulness; and reduced product loss, production cost, and air pollution in California. Feedback was collected from interested parties of food processors. Two demonstration tests were carried out at the production facility of Treasure8, Richmond, California in 2017 with the SIRDBHAD system on August 4, 2017 and November 16, 2017.

## On Site Demonstration

A demonstration was arranged for advisory committee members, fruit and vegetable processers, processing equipment manufacturers and researchers on August 4, 2017 at Richmond, California. Figures 39 to 47 show the different activities with the participants. The participants were explained the objectives of the project, detailed information about the design and operation of individual components of the dryer, and the operation of the dryer with different vegetable and fruit snacks. Benefits of the dryer and the resulting healthy snacks were also given. The visitors were provided with healthy snack samples for sampling and their feedback was received about the snack quality, including appearance (color), crispness, taste and flavor. The snacks were prepared from vegetables and fruits, including carrot, squash, kale, apple, sweet potato, bell pepper and pear. Participants were impressed by the operation of the new SIRDBHAD system and the taste and flavor of the chips.  Findings of the project, including reduction in drying time, savings in natural gas and electricity consumption, quality improvement and reduction in drying cost, were presented.

**Figure 39: Dr. Pan Explains the Operation of the SIRDBHAD System to the Visitors**

*Source: University of California, Davis*

**Figure 40: Participants Seeing the Operation of IR Dryer Unit During Demonstration**

*Source: University of California, Davis*

**Figure 41: Dried Apple Chips from SIRDBHAD System**

*Source: University of California, Davis*

**Figure 42: Dr. Pan Shows the Healthy Snacks Samples Prepared from Fresh Fruits and Vegetables**

*Source: University of California, Davis*

**Figure 43: Participants Taste the Healthy Snacks Prepared Using the SIRDBHAD System**

*Source: University of California, Davis*

A demonstration was arranged for the CEC Project Manager, Kevin Mori on November 16, 2017 at Richmond, California. The project progress was presented and discussed before the demonstration. Detailed information on the design and operation of individual components of the dryer was given, and dryer processing of different vegetable and fruit snacks was shown. They were also shown the operation of different components, including the slicer, IR dryer, hot air dryer and ambient air cooler. The snacks prepared from vegetables and fruits including carrots, apples, sweet potatoes, bell peppers and pears were offered for tasting. Findings of the project, including reduction in drying time, savings in natural gas and electricity consumption, quality improvement and reduction in drying cost, were presented.

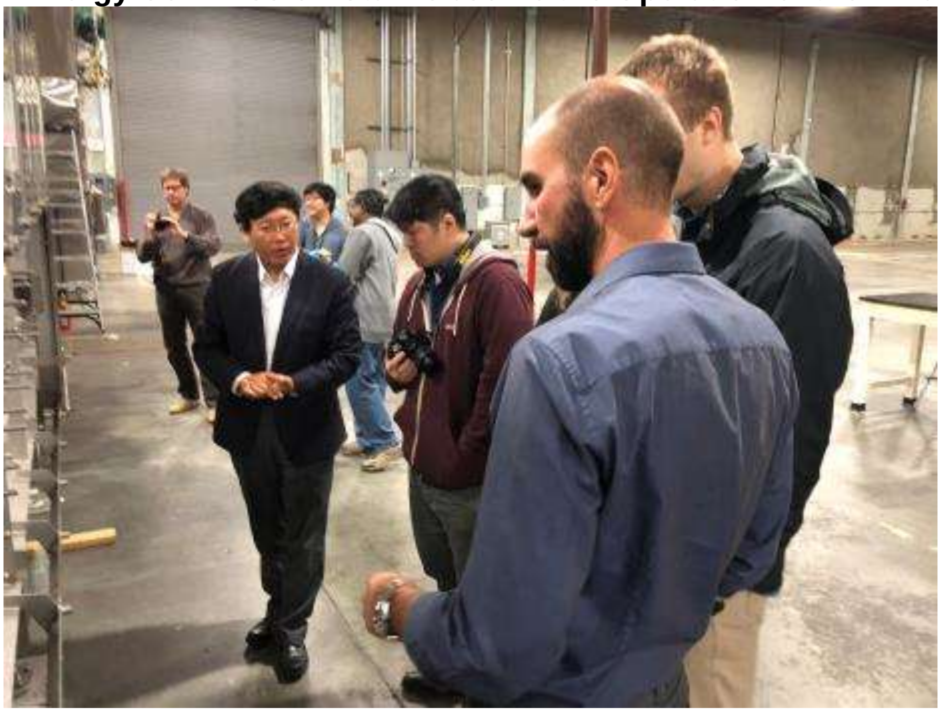
**Figure 44: Research Team and Energy Commission Staff Watch the Operation of the Fruit and Vegetable Slicer**

*Source: University of California, Davis*

**. Figure 45: Professor Pan Explains the Operation of Slicer and Feed Conveyor**

*Source: University of California, Davis*

**Figure 46: Energy Commission Staff Observe the Operation of the Infrared Dryer**



*Source: University of California, Davis*

**Figure 47: Dr. Pan Explains the Operation of Hot Air Dryer to Energy Commission Project Manager Kevin Mori**

*Source: University of California, Davis*

## Conclusions

The commercial scale SIRDBHAD system was demonstrated on two separated days. The demonstration was attended by food processing company executives, drying equipment manufacturers, researchers and the project manager from the California CEC. The participants were actively involved in understanding the working of various components of the SIRDBHAD system and tasting the fruit and vegetable chips prepared by the dryer. The advantages of the new technology in energy and water savings over the current practice of water blanching and hot air/freeze drying were explained to the participants. Health benefits of eating vegetable and fruit snacks, including obesity prevention, were discussed with the participants.

# Dissemination of Technology

## UC Davis Picnic Day

The novelty of the SIRDBHAD technology to simultaneously perform the dry-blanching and drying to produce the healthy, crispy and crunchy dried chips were disseminated to the fruit and vegetable processers and the consumers by poster presentations, demonstrations, videos and dried sample displays at the UC Davis Picnic Day 2017 on April 22, 2017.  The poster displayed at the UC Davis Picnic Day is shown in Figure 48.

**Figure 48: UC Davis Picnic Day 2017 Poster of the SIRDBHAD System Installed at Richmond, California**


*Source: University of California, Davis*

## CLFP EXPO 2018

The SIRDBHAD system was demonstrated to the participants of the California League of Food Processors (CLFP) Expo 2018 held in February 21-21, 2018 at Sacramento through poster display, brochure, and Virtual Reality videos produced by Sense8xr.com. The SIRDBHAD dried chips of sweet potatoes and apples were provided to the fruit and vegetable processors, growers and consumers (Figures 49-51). The products and the videos attracted several processers and growers. The technology was very much appreciated for its suitability to produce healthy chips with water and energy saving as indicated by the feedback of the visitors.

**Figure 49: Poster Displayed at CLFP Expo 2018 of SIRDBHAD Technology**


*Source: University of California, Davis*

**Figure 50: Brochure on SIRDBHAD Technology Distributed at CLFP Expo 2018**


*Source: University of California, Davis*

**Figure 51: The CLFP Expo Booth Showing the SIRDBHAD Dried Chips Provided for Tasting**


**From left to right: Professor Pan, Chandrasekar Venkitasamy and Timothy Childs.**

*Source: University of California, Davis*

## Conference Presentations

The results of this project were published through conference presentations and peer reviewed journal publications.

- Chen, J., C. Venkitasamy, Q. Shen, T.H. McHugh, R. Zhang and Z. Pan. 2018. Development of Healthy Crispy Carrot Snacks Using Sequential Infrared Blanching and Hot Air Drying Method. LWT – Food Science and Technology, 97: 469-475
- Chen, J., C. Venkitasamy, Q. Shen, T.H. McHugh, and Z. Pan. 2017. Effect of infrared dry-blanching and hot air-drying on the physical properties of healthy crispy carrot snacks. Presented at the IFT Annual Meeting. June 25-28. Las Vegas, Nevada. Poster Presentation.
- Chen, J., C. Venkitasamy, Q. Shen, T.H. McHugh, and Z. Pan. 2016. Development of healthy crispy carrot snacks using sequential infrared dry-blanching and hot air-drying methods. Presented at the IFT Annual Meeting. July 16-19. Chicago. IL. Poster presentation.
- Pan, L., C. Venkitasamy**,** Z. Pan, and T.H. McHugh. 2016. Drying and quality characteristics of kale under infrared heating. Presented at the Annual International Meeting of ASABE. July 17-20. Orlando, FL. Poster presentation.

# LIST OF ACRONYMS

| Term | Definition |
|---|---|
| $^{o}C$ | Degrees centigrade |
| CDFA | California Department of Food and Agriculture |
| CIR | Catalytic infrared radiation |
| CLFP | California League of Food Processors |
| CEC | California Energy Commission |
| FIR | Far infrared |
| g | Grams |
| GHG | Greenhouse gas |
| HA | Hot air |
| IR | Infrared |
| kg | Kilogram |
| $kW/m^2$ | Kilowatts per square meter |
| kWh | Kilowatt-hour |
| M | Moles |
| MC | Moisture content |
| µL | Microliter |
| µm | Micrometer |
| MIR | Medium infrared |
| ml | milliliter |
| mm | Millimeter |
| mM | mill moles |
| MR | Moisture ratio |
| NIR | Near infrared |
| nmNOx | Oxides of nitrogen |
| POD | Peroxidase |
| $R^2$ | Coefficient of regression |

| Term | Definition |
|---|---|
| RMSE | Root mean square error |
| rpm | Revolutions per minute |
| s | Seconds (time) |
| SIRDBHAD | Sequential infrared dry-blanching and hot air drying |
| UC | University of California |
| USDA | United States Department of Food and Agriculture |
| w.b. | Wet basis |

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