EFFECT OF PRE AND POST-HARVEST TREATMENTS ON CHARACTERISTICS OF 'PAWNEE' PECAN KERNELS

A Thesis

by

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Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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May 2014

Major Subject: Horticulture

ABSTRACT

The Hunter Lab color system and three visual rating scores (class 1 is the best) were used in this study to evaluate kernel color change and speckling, respectively, in ‘Pawnee’ pecan [*Carya illinoinensis* (Wangenh.) K. Koch] kernels. Three harvesting practices (‘Direct’, early harvest and brought to the lab; ‘Cluster’, late harvest; and ‘Ground’, early harvest and kept on the ground of the orchard), four storage temperature combinations [oven at 80 °C for 48 h then ambient temperature (‘OA’), continuous ambient temperature (‘AA’), ambient temperature then refrigeration at 6 °C (‘AR’), oven at 80 °C for 48 h followed by refrigeration (‘OR’)], and two shelling dates were conducted. Results indicated that ‘Direct’ and ‘AR’ treatments in the first shelling date were lighter and had more color saturation with less class 2 and 3 speckling. In contrast, 'Ground’ and ‘OA’ treatments in the second shelling date were darker, and had less saturated color with a greater amount of dark spots. Another study was conducted to further understand the reasons of color changes and speckling appearance in ‘Pawnee’ kernels. Samples were subjected to four accelerating conditions (puncture, temperature, shelling, and storage time) assuming these might be positively correlated to reduced kernel color quality. The outcomes of this study implied that lightness, hue, and Chroma values were greater in 0 week of storage, shelled pecan, 25 °C, not punctured kernel treatments and decreased in the three week, unshelled, and 40 °C, punctured kernel treatments. Color changes were mostly related to the changes in lightness and hue, and to a lesser extent the changes in Chroma. Kernels from class 2 and class 3 of visual

rating scale increased with an increase in the time of storage, accompanied with higher temperature. No significant effect was found for puncture or shelling treatments on speckling in ‘Pawnee’ pecan kernels.

DEDICATION

First, I want to dedicate this thesis to two beloved people who mean so much to me, although they are no longer in this world. They are my parents who raised me, loved me, and taught me. I will never forget you.

I also want to dedicate this to my husband Maad who has been a great source of motivation and inspiration. Finally, I dedicate my thesis to my three children Dalia, Shams, and Zaid. I love you all.

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to Dr. Leonardo Lombardini for his support and guidance throughout the courses of my study. Very special thanks go to Dr. Luis Cisneros and Dr. David Byrne for their suggestions and encouragement during the research project. Also, I am grateful to Monte Nesbitt for providing ideas about my research, Dr. Astrid Volder for her overwhelming assistance with using the image software and opening her lab to me, and Dr. Elena Castell-Perez for providing me with the laboratory facilities that I needed in collecting colorimeter data.

The deepest thanks go out to my husband, Maad Rawendoozi, for his constant encouragement to achieve this goal and his help in my statistical analyses. Finally, I would really like to thank my three children, Dalia, Shams, and Zaid, for their patience during the time of my study.

TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

Introduction

Pecan [*Carya illinoinensis* (Wangenh.) K. Koch] is a member of the Juglandaceae family that has been known for centuries for its edible nuts and is the most valuable nut tree native to North America (Hall, 2000). It is a species distributed over an area of geographic and climatic variation extending from northern Illinois and southeastern Iowa to the Gulf coast of the United States (Thompson and Grauke, 1991). This riparian species grows abundantly along the Mississippi River, the rivers of central and eastern Oklahoma, and the Edwards Plateau in Texas. Today, pecan is commercially produced outside its native range in Georgia, California, Arizona, New Mexico, and western Texas where environmental conditions can differ from those of its native range.

Today, pecan is one of the most important commercial nut crops grown in the United States (Geisler, 2011). With the absence of actual world pecan production statistics, the United States is considered to be the world's largest producer. The Combined production of the United States and Mexico is estimated to be 90-95% of the world's pecans (Johnson, 1997). Out of the 14 major commercial pecan production states, Georgia, Texas, and New Mexico produce more than 72% of U.S. total pecans (U.S. Department of Agriculture, 2012). More recently, the cultivation of pecan has been extended to countries in South America, Asia, South Africa, and Australia (do Prado et al., 2013; Venkatachalam et al., 2007).

Pecans, like most nuts, are a good source of proteins, are cholesterol-free, and low in sodium (Silva et al., 1995). Their lipid content is between 65.9 and 78.0% and high in unsaturated fatty acids (Venkatachalam, 2004). Pecans are considered a healthy food because of the high monounsaturated fatty acid content (Villarreal-Lozoya et al., 2007) and high concentrations of phenolics, flavonoids, and proanthocyanidins, which are phytochemicals with strong antioxidant properties (de la Rosa et al., 2010). Pecans protect against ischemic heart disease (IHD), increase longevity (Sabaté, 1999), and can lower total cholesterol and low-density lipoproteins LDL or "bad cholesterol" (Morgan and Clayshulte, 2000). Also, because of the antioxidant capacity of the phenolic compounds, they can reduce the incidence of some chronic diseases, such as Alzheimer's, Parkinson's, and some cancer types (Mertens-Talcott and Percival, 2005; Tam et al., 2006; Wu et al., 2004).

Pecan kernels have a wide range of possible uses. They can be sold in shell or shelled, and used as a main ingredient for confectionery, dairy and bakery products. Other uses include: incorporation into snack bars in raw form, sweetening by coating with honey or sugar, salting, roasting, spicing, and for improving and finishing processed products (Swink, 1996).

Quality and stability

Pecan kernels are a semi-perishable product that needs to be refrigerated to maintain their quality and extend shelf life (Senter et al., 1980). Post-harvest quality of pecan kernels has been studied and research has been conducted to minimize storage

cost through pecan handling, processing, and storage (Heaton and Shewfelt, 1976; Woodroof and Heaton, 1961). Kernels are subject to undesirable oxidation processes because of the high content of unsaturated fatty acids (Senter and Horvat, 1976). Oxidation results in rancidity and off-flavors, which can make kernels unmarketable (Baldwin and Wood, 2006).

Pecan nuts lose quality very quickly on the ground, especially if exposed to wet conditions, and can oxidize or turn rancid more rapidly in light and out of their shell. Consequently, they are best stored in a cool, dry, protected location (University of Arkansas System, 2013). Woodruff (1979) reported that the best flavor of pecan kernels develops within a short time after harvest and declines slowly throughout storage period. He also suggested that the loss of quality starts with production of volatile components, color darkening, onset of stale flavors and aroma development due to oxidation. Subsequently, fat hydrolysis increases the proportion of free fatty acids which cause the development of acrid flavors. After harvest, the moisture content of the kernels should be rapidly reduced to 3.5-4.0% which helps delay the incidence of quality loss (Woodruff, 1979). However, the quality of pecans can be preserved for up to 3 years if stored at -2 °C or below (Heaton, 1974).

Kernel color, flavor, thickness and size, oil content, and absence of contaminants are the major pecan quality measures. Despite the fact that a dark or light color does not necessarily indicate poor or good quality, respectively (Arnold and Baker, 1982), kernel color remains an important factor in quality determination in the pecan trade, and producers tend to offer bright golden-colored kernels for consumers to maintain the price

structure. The market value of pecans, particularly for shellers, greatly depends on the color of the kernel, with a dark color generally associated with age and rancidity (Goff, 1992; Hubbard et al., 1991). Lighter kernels obtain higher grades and are priced higher than darker kernels (Kays, 1979; U.S. Department of Agriculture, 1980). The price paid to pecan growers in the Southeast was $\$2.58.kg^{-1}$, $\$2.05.kg^{-1}$, and $\$1.50.kg^{-1}$ for fancy, standard, and amber kernels, respectively, as an average for the period 1973 – 1977 (Kays, 1979), compared to $\$1.24.kg^{-1}$paid for unshelled pecans averaged for the period 1974 – 1976 (U.S. Department of Agriculture, 1977)

Kernel color, however, is not always an accurate measure of quality because it is also a cultivar characteristic and can range from a very light cream color to a darker brown. The color of the pecan kernel greatly depends on the cultivar and harvest conditions (Kays and Wilson, 1978). Light-colored kernels can darken if handled improperly and exposed to poor quality storage conditions. Kernels harvested early, properly dried, and stored in cool storage temperature will retain quality and color for a longer period of time. Pecan kernel quality will degrade quickly if nuts are left on the wet ground (Goff, 1992).

Pecans are graded according to their color; light (golden color), light amber (light brown), amber (medium brown), and dark amber (dark brown). A light color indicates fully mature pecans that have been harvested, processed, and stored properly. A darker color is caused by exposure of the kernels to adverse conditions, which in turn can trigger the nuts to synthesize enzymes, phenolic compounds and condensed tannins

which will react in oxidative processes (Balasundram et al., 2006; Shahidi and Naczk, 2004).

Factors affecting color changes and loss in quality characteristics

The development of color in the pecan kernel takes place after the beginning of the shuck dehiscence period, when the nuts are still on the tree (Kays and Wilson, 1977). Reflectance values showed that L-value (lightness) gradually decreased in the first 9 weeks when the developing kernel is $^{1}/_{2}$ to $^{2}/_{3}$ of its final size (Kays and Wilson, 1978). Most of the extractable pigments are located exclusively in the testa (i.e., the seed coat) of the kernel (Kays and Wilson, 1977). Tannins, carotenoids and their oxidized products and by-products are the common compounds that are responsible for kernel color. The contribution of carotenoids in the kernel color is small (0.9-1.5 $\mu g \cdot g^{-1}$ of lipid) (Kays, 1979). Tannin pigments are the major molecules in the kernel testa and also contribute to the color (Woodruff, 1979). The seed coat (testa) usually absorbs tannins from the middle septum portion of the pecan nut hull (Brison, 1974). Tannins of different degrees of polymerization can be found in hydrolyzed and condensed (proanthocyanidins) forms (Santos-Buelga and Scalbert, 2000). Tannins are also present in high amounts in pecan shells and it is believed that that they are leached into the kernel of the pecans during pre-conditioning, before shelling (Villarreal et al, 2007). These compounds have an impact on stability of color and flavor of nuts (Heaton et al., 1975).

Many factors affect the rate and level of color development in pecan kernels, including cultivar (Forbus Jr. et al., 1983), time of harvest (Heaton et al., 1975; Kays and

Wilson, 1977), curing methods (Heaton et al., 1975), time in storage (Forbus Jr. et al., 1983), moisture content in the kernel (Heaton and Woodroof, 1970), and whether they are stored shelled or unshelled (Kays and Wilson, 1978).

Kernel color quality is affected by the time between dehiscence stage and harvest. Quality kernels with lighter, uniform and stable color are often obtained when nuts are harvested early and dried properly. These kernels are also subject to slower changes throughout storage (Heaton et al., 1975). On other hand, nuts that are subjected to physical damages during harvest and post-harvest processes will result in darker kernels (Reid and Heaton, 1977).

Growing conditions. Environmental and growing conditions can affect kernel color within a cultivar. Color also varies with fatty acid composition, which is sensitive to variation in crop load (Storey et al., 1995). Differences in kernel color over a 3-year period were attributed to changes in the weather conditions such as precipitation and humidity during the growing season (Heaton et al., 1975).

Moisture. Moisture is considered a major contributor to decreasing kernel quality. Higher levels of moisture may darken pecans stored Unshelled as a result of the migration of tannins from the shell lining to the kernel (Wagner, 1980). Additionally, high moisture levels of shelled pecans have a positive correlation with respiration rates which may shorten the length of the shelf-life (Santerre, 1994). Lowering moisture below the levels that are considered safe during storage can be advantageous to minimize respiration rate and mold growth, but it can have negative consequences for inducing instability of membranes. This causes structural damage and may subsequently

cause kernel testa to be easily cracked and more subject to oxidation (Beaudry et al., 1985). Soil and air moisture levels at harvest can also affect the color of kernels. Nuts that are left on the ground can be discolored if soil surface is humid (Heaton et al., 1975). Drying pecans with warm (below 40 °C) dry air circulating around the nuts results in excellent color, texture, flavor, and oil stability (Heaton and Woodroof, 1970).

Temperature. Temperature is the most crucial factor affecting the shelf life of unshelled and shelled pecans. The greatest benefit of storing at low temperature is retention of the fresh flavor, aroma, texture, and bright color (Herrera, 2005). Color, flavor, and appearance were maintained for 25 years when kernels were stored at -20 °C in hermetically sealed containers (Hao et al., 1991). Although freezing or refrigeration are suitable methods for prolonged pecan storage, they are not suitable for some pecan-containing products that are usually stored at ambient conditions such as breakfast cereals and cookies (Santerre, 1994).

It is well known that high temperature storage increases unwanted biochemical reaction rates. Temperatures above 4.4 °C cause relatively quick discoloration in kernels (Hao et al., 1991) and slight staleness and rancidity were detected after just one week of storage at 37.8 °C (Heaton et al., 1977). Unfavorable storage conditions can also result from temperature fluctuations, particularly when temperature of the storage environment falls below the dew point.

Shelling. The process of shelling pecans involves washing, sanitizing, cracking, and separating kernels from shells. Shelling has been proven to lessen the shelf life of the nuts. Researchers reported that the quality was maintained in shelled pecans stored at

22 °C for three to four months (Woodroof and Heaton, 1967). On the other hand, Unshelled pecans could be stored for six months at the same temperature (Woodroof and Heaton, 1967). Kay and Wilson (1978) investigated the relationship between shelling and the color of the testa in kernels of several pecan cultivars. Results showed that shelled pecan kernels stored at room temperature in open trays were darker than unshelled pecans, and color transformation was at its greatest after 4 weeks (Kays and Wilson, 1978).

Light. Pecan kernels are usually displayed in stores in packages to allow consumers to observe and select the product. However, exposure to sunlight is another factor that reduces storage life of pecans. Lightness of kernel color was reduced by 21% after 24 h of exposure to sunlight, and darkening was significant after only 4 h of exposure to sunlight (Heaton and Shewfelt, 1976). However, exposure to cool white fluorescent light had less effect than sunlight, due to the absence of ultraviolet light.

Oxygen. Oxygen is one of the factors that can cause the highest degree of discoloration and rancidity in pecan kernels. Dull and Kays (1988) reported that pecan kernels stored in foil pouches impermeable to oxygen for 24 weeks developed a slightly acid flavor due to greater anaerobic respiration the kernels undergo, suggesting that the materials for packaging of pecans must allow oxygen transmission rates above 0.08 $cc \cdot 100\ cm^{-1} \cdot 24\ h^{-1}$. To determine the effects of low oxygen (1.6%) environments on quality, pecan kernels were stored in impermeable bags with oxygen-absorbing compounds at 38 °C (Santerre et al., 1990). After 43 days of storage in oxygen limited

conditions, kernels became darker and softer, and a 'fruity' flavor was obtained after 52 days (Santerre et al., 1990).

Oxygen is also required for metabolic activities to occur. Oxygen concentration and temperature of the storage are major factors determining the effect of oxygen. Storage of pecan kernels at low temperature limits the effect of high oxygen concentration and makes it less critical as low temperature inhibits the oxygen reaction rates in the kernel tissues. Storage at very low levels of oxygen may result in the reduction of quality due to the onset of anaerobic conditions, leading to undesirable reactions and distinct off-flavors (Dull and Kays, 1985).

Edible coatings, such as hydroxypropyl cellulose (HPC) and carboxymethyl cellulose (CMC), can be used to reduce rancidity by acting as a barrier to gas exchange and thus restricting oxygen contact with kernel-associated fats (Baldwin and Wood, 2006). However, these experimental methods are costly and have not been adopted by pecan processors. Because the discoloration of the testa in pecan kernels is caused by the oxidation of tannins to their respective derivatives (Senter et al., 1978), storing at low oxygen concentration (2%) maintained the optimum kernel color (Kays, 1979).

Time of harvest. Harvesting shortly after the packing tissue between the kernel halves turns brown produces the highest quality walnuts (Sibbert et al., 1974). This may also be the case with producing high quality pecans (Woodroof and Heaton, 1961). Harvesting too early can also have negative consequences on kernel quality. Pecans that were harvested before their shells turned brown were poorly filled, low in weight, and tough to shell (Heaton and Woodroof, 1970).

Kernel darkening begins around shuck split and continues throughout the harvest period. Pecans that are harvested quickly after shuck split, promptly dried, and refrigerated provide better quality color and flavor stability than those harvested later because nuts are less exposed to severe weathering conditions such as cycles of drying and re-wetting. Kernels of 'Schley', 'Stuart', and 'Wichita' pecan cultivars harvested early were lighter in color than kernels that were delayed. Thus, early-harvested nuts usually have that lighter color that is preferred by the trade (Heaton et al., 1975).

Sanitization. Conventional sanitization approaches are a big challenge for the pecan industry. The use of chlorine and hot water can negatively affect quality of pecan (Erickson et al., 1994). Recently, irradiation treatments, such as E-beam irradiation, have been applied to various commodities, including pecan (Villarreal-Lozoya et al., 2009) Results indicated that there was no significant difference between the color of treated and control kernels, indicating that this method could be utilized for pecan sanitization without impacting the quality (Villarreal-Lozoya et al., 2009).

Packaging. In the pecan industry, packaging is vital for handling, storage, transportation, and marketing. The role of packaging is not limited to holding the nuts but it should provide protection from all the deterioration that can occur during post-harvest processes. The majority of packaging materials allows some movement of oxygen and water molecules. Pecans maintained acceptable quality for more than 6 months of storage at 24°C and 60% RH in a poly-vinylidenechloride coated cellophane packaging film with low oxygen transmission rates (Dull and Kays, 1988). The same

researchers reported that kernel color was maintained and mechanical damage was significantly decreased with vacuum packaging, however, flavor was adversely affected.

Measuring color

Various classification systems have been used to describe kernel color in pecans. In Texas, a five-class system relies on a photograph of five kernels, each representing a color class (McEachern et al., 1994). However, the U.S. standards for grading shelled pecans consist of four grades based on skin color of the pecan kernel. “Light” means that the outer surface of the kernel is mostly golden color or lighter, with not more than 25% of the outer surface darker than golden, none of which is darker than light brown. “Light amber” means that more than 25% of the outer surface of the kernel is light brown, with not more than 25% of the outer surface darker than light brown, none of which is darker than medium brown. “Amber” means that more than 25% of the outer surface of the kernel is medium brown, with not more than 25% of the outer surface darker than medium brown, none of which is darker than dark brown (very dark-brown or blackish-brown discoloration). “Dark amber” means that more than 25% of the outer surface of the kernel is dark brown, with not more than 25% of the outer surface darker than dark brown (very dark-brown or blackish-brown discoloration) (U.S. Department of Agriculture, 1969).

Several techniques have been used by scientists to measure pecan kernel color. Colorimeters such as those manufactured by HunterLab have been widely used to measure the color of fruits and vegetables. These instruments correctly determine

lightness (*L*). Two other coordinates (*a* and *b*) are related, and indirectly reflect the visually informative parameters of hue and Chroma (Thompson et al., 1996)

The Hunter *L*, *a*, *b* color space is organized in a cube form as shown in Fig. 1 below:

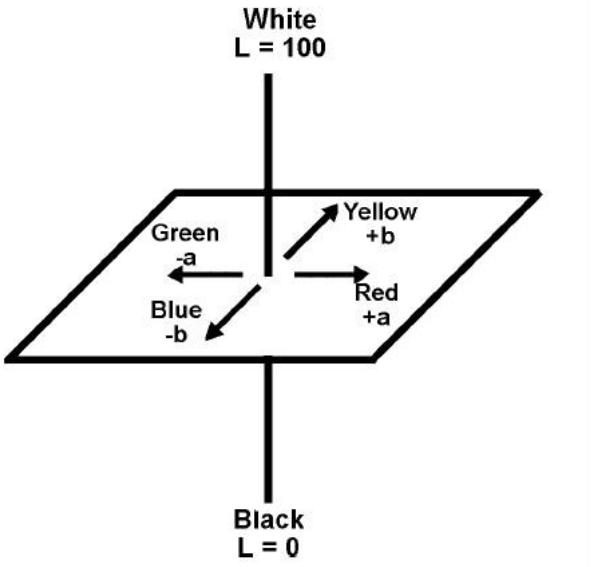

Fig. 1. Hunter *Lab* color space organization (HunterLab, 2008)

The lightness axis (*L*) goes from a minimum value of 0 (which corresponds to black) to a maximum value of 100 which corresponds to white. The redness (*a*) and yellowness (*b*) axes have no specific numerical limits. Positive and negative values of *a* are red and green, respectively, while positive *b* is yellow and negative *b* is blue (HunterLab, 2008).

‘Pawnee’

‘Pawnee’, a cross of 'Mohawk' and 'Starking Hardy Giant' released in 1984, is an early maturing, high quality pecan cultivar with light colored kernels. This pecan cultivar is one of the most cultivated pecan variety grown throughout the U.S. pecan belt (Grauke and Thompson, 2012). There are no other cultivars to compete with ‘Pawnee’ in the early market because of its early ripening (Wells and Conner, 2012); however, this cultivar has some tendency to bear nuts biennially . Nuts typically mature in the latter half of September in Texas. The plants are susceptible to scab, have a fair resistance to downy spot (Grauke and Thompson, 2012), and outstanding resistance to the black margined aphid, a major insect pest of pecan (Thompson et al., 2000). This variety is recommended for planting across Texas, Oklahoma, Kansas, to Alabama and Arkansas (Grauke and Thompson, 2012). On the other hand, ‘Pawnee’ kernels frequently are characterized by the development of a dark necrotic area at the basal end of the kernel. The cause of this problem is still unknown (Smith, 2012). Also, the testa of ‘Pawnee’ kernels typically develop an unattractive speckling that affects kernel appearance and acceptance by consumers (Sparks, 2014). The color of ‘Pawnee’ kernels, however, darkens quickly in storage, and kernels will stain if the nuts are rained on after shaking the trees, requiring a prompt harvest to retain maximum quality (Wells and Conner, 2012). Furthermore, some growers have complained about the appearance of speckling on the testa of ‘Pawnee’ kernels, which may affect and prohibit the use of ‘Pawnee’ pecans in the gift-pack trade.

Objective

This study was conducted to investigate if time of harvesting and post-harvest conditions (temperature and storage time) affect the color and speckling occurrence on 'Pawnee' kernel. We hypothesized that speckling occurrence and can be minimized by prompt harvesting and implementation of optimal post-harvest handling treatments (low storage temperature, reduced storage time, presence of shell).

CHAPTER II

MATERIALS AND METHODS

Experiment 1

The fruits (referred to as 'nuts' from here on) used for this study were collected in 2011 in a commercial pecan orchard located in Hempstead, TX (lat. 29°56'17.04" N, long. 96° 7'11.29" W, altitude 42.5 m). Three mature 'Pawnee' trees were chosen based on uniformity of size, vigor and crop load. Average trunk diameter of chosen trees was 25.9 ± 1.4 cm.

Sixty-four pecan nuts were manually harvested at shuck split stage (24 Sept. 2011) from each tree. Half of the harvested nuts were placed on the orchard floor next to the trunk of the tree ('Ground' treatment) from which they were harvested and covered with metal cages to protect them from predators. Two temperature sensors (HOBO Pendant Temperature/Light Data Logger UA-002-64, Onset Corp., Cape Cod, MA) were placed in two of the cages and programmed to record air temperature at 10-min intervals. The remaining 32 nuts were labeled and brought back to the laboratory on the same day ('Direct' treatment). A few additional fruit clusters were selected from each tree and wrapped with a fine cloth (tulle) tight enough to prevent shuck opening and fruit fall ('Cluster' treatment). Two additional temperature sensors (HOBO) were tied on the tree branches next to the selected clusters and also programmed to record air temperature at 10-min intervals.

Once in the laboratory, each group of 32 nuts/tree was divided into four groups of eight nuts and grouped with those from the other trees. The four 24-nut groups were

then weighed and assigned to different post-harvest treatments as indicated in the following scheme (Fig. 2):

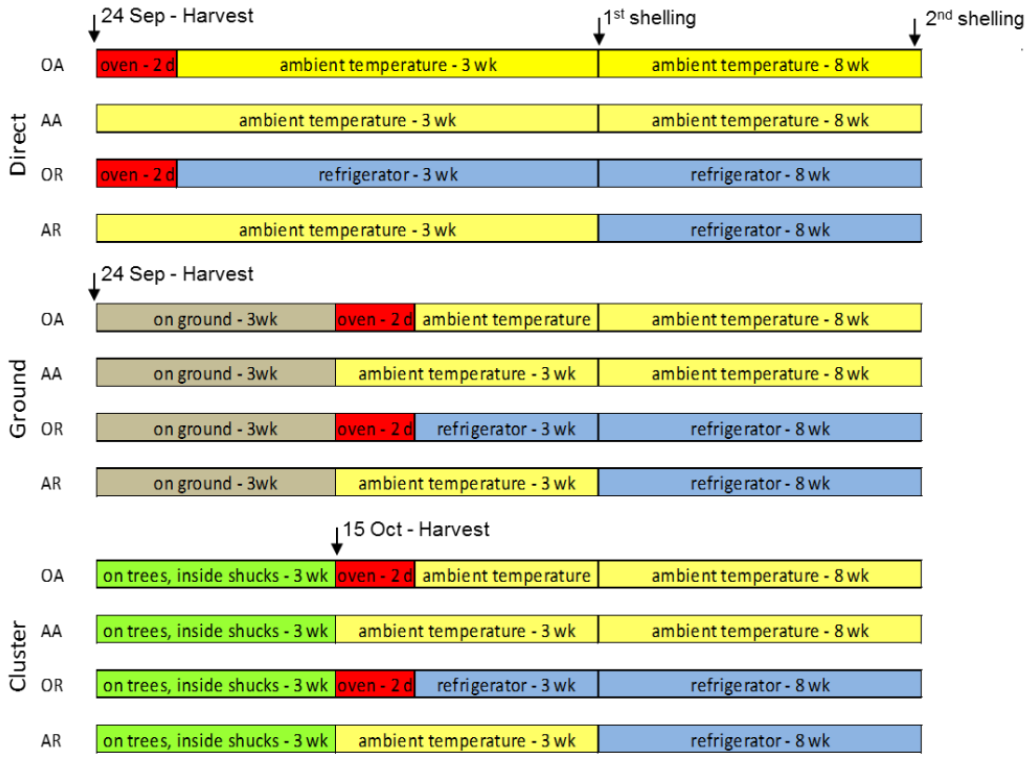

Fig. 2. Treatment scheme of experiment 1

The nuts from the first group (OA) were placed in the oven at 80 ºC for 48 h for fast drying and then left at room temperature on the lab bench for 3 weeks. The nuts from the second group (AA) were left at room temperature on the lab bench for 3 weeks for slow drying. In the third group (OR), nuts were placed in the oven at 80 ºC for 48 h for fast drying and then moved to the refrigerator at 6 ºC for 3 weeks. Nuts from the fourth group (AR) were left on the lab bench at room temperature for slow drying for 3

weeks. Two additional HOBO sensors were placed on the lab bench and in the refrigerator to record the temperature for each sub-group.

Three weeks after placing the nuts on the lab bench or in the refrigerator, half of the nuts from each group were cracked and shells were carefully separated from the meat to determine kernel characteristics and percentage. On the same day, the remaining 12 nuts of all treatments were weighed and left in the same conditions except group AR which was moved to the refrigerator at 6 ºC for 8 weeks.

A colorimeter (LabScan XE 16437, HunterLab, Inc., Reston, VA) was used to assess changes in color of the pecan half-kernels using the CIELAB system. The measuring aperture diameter was 36 mm, and D65/10° was the illuminant/viewing geometry. The colorimeter was calibrated using the standard white and black plates.

Eight weeks after first shelling date, the remaining nuts were cracked and kernels were separated from the shells. Half-kernel color was measured using the same color meter as described above.

On 15 Oct. 2011, the 32 ‘Ground’ nuts/tree were collected from the orchard and taken back to the laboratory. On the same day, the 32 ‘Cluster’ nuts/tree were removed from the shucks and taken to the laboratory. Once in the laboratory, ‘Ground’ and ‘Cluster’ nuts were divided in four groups and subjected to the same treatments and measurements as indicated above for ‘Direct’ nuts.

Percentage of dark spots area on each half-kernel was assessed visually. A visual rating scale was used to assign the occurrence of speckling on ‘Pawnee’ half-kernels to three classes: Class 1 (low) when speckles covered 0–2% of the area and were not

noticeable with the naked eye, Class 2 (medium) having speckles on 2-5% of the area, and Class 3 (severe) with speckles on more than 7% of the area (Fig. 3). The observations were made in a laboratory setting with overhead fluorescent lighting.

Class 1 Class 2 Class 3

Fig. 3. Visual scale of speckling occurrence in pecan half-kernel. Class 1 (Low): speckles covered 0–2% of the surface and were not noticeable with the naked eye. Class 2 (Moderate): speckles covered 2-7% of the surface; Class 3 (Severe): speckles covered more than 7% of the surface.

Half-kernels were photographed with a digital camera (D50, Nikon Corp., Tokyo, Japan), and the images were analyzed using the color analysis feature of WinRhizo Pro software (v2009c; Regent Systems, Quebec, Canada). Dark area was assigned to speckling and the rest was assigned to the healthy area. The software was used to measure and determine total kernel area, total dark area, and the percentage of speckled area.

Experiment 2

'Pawnee' nuts were purchased from a commercial pecan orchard located near Wichita Falls, TX (lat. 34° 5'54.60"N, long. 98°19'19.93"W, altitude 291 m) in 2012. Nine hundred sixty nuts were divided into 2 groups of 480 nuts and assigned to "shelled" and "Unshelled" treatments to study the effect of shelling on kernel color change. Each of these two groups were divided into two sub-groups of 240 nuts and assigned to be placed at 25 °C and 40 °C in order to determine the role of temperature on speckling and kernel color change. Each of the sub-groups were also divided into two sub-sub groups and assigned to "punctured" and "not punctured" treatments, to understand the role of micro lesions on speckling development. In the Unshelled group, nuts were kept unshelled for 1 week at designated temperatures (25 and 40 °C) before shelling and puncturing.

For the punctured group, a small needle was used to make several punctures on the dorsal side of the half-kernel. The following scheme (Fig. 4) shows the arrangement of the 32 30-nut groups. The same measurements as in Experiment 1 were taken.at 0, 1, 2, and 3 weeks from the start of the experiment.

960 nuts								
Shelled (480 nuts)				**Unshelled** (480 nuts)				
40 ^{0}C		25 ^{0}C		40 ^{0}C		25 ^{0}C		
Shelled and kept at the designated temperatures for 1 week				Kept **In-shell** at the designated temperatures for 1 week				
Not punctured	Punctured	Not punctured	Punctured	Not punctured	Punctured	Not punctured	Punctured	Storage (week)
60 halves	60 halves	60 halves	60 halves	60 halves	60 halves	60 halves	60 halves	0
60 halves	60 halves	60 halves	60 halves	60 halves	60 halves	60 halves	60 halves	1
60 halves	60 halves	60 halves	60 halves	60 halves	60 halves	60 halves	60 halves	2
60 halves	60 halves	60 halves	60 halves	60 halves	60 halves	60 halves	60 halves	3

Fig. 4. Treatment scheme of experiment 2.

Statistical analysis

Data was subjected to analysis of variance (ANOVA) and means were separated by Tukey's honestly significant difference (HSD) method at $P \leq 0.05$. Chi Square test at $P \leq 0.05$ was performed on the pooled data for significant factor effects on speckling classes. Regression analysis and Pearson correlation coefficient was used to compare the actual and visually rated speckled area. All statistical analyses were conducted using JMP software (v. 9.0.0, SAS Institute, Inc., Cary, NC,).

CHAPTER III

RESULTS AND DICUSSION

Experiment 1

Lightness values were significantly affected by the interaction among location, post-harvest, and shelling date treatments. Values ranged from 27.9 in 'Direct' 'AR' in the 1st shelling date to 23.3 in 'Ground' 'OR' in the 2nd shelling date (Table 1). Most of the half-kernel lightness values were higher in 'Direct' location and decreased in 'Cluster' and 'Ground' locations in both shelling dates; however, this decrease became more obvious and significant on the 2nd shelling date for 'AA', 'OR', and 'OA' in which lightness values decreased from 25.1, 25.5, and 25.4 in 'Direct' location to 23.3, 23.3, and 23.6, respectively. No significant differences were observed between 'Direct' and 'Cluster' locations for all corresponding post-harvest treatments at both shelling dates. Lightness values decreased in the 2nd shelling date of 'Ground' location in all post-harvest treatments, except for 'AR' and 'OA'. This may be attributed to the effect that refrigeration had on the nuts, which were placed in the refrigerator for 11 weeks prior to the 2nd shelling date. According to Herrera (2005), the greatest benefit of storing at nuts at a low temperature is the retention of a bright color, as well as fresh flavor, aroma, and texture. Other research shows that freezing or refrigeration are suitable methods for prolonged pecan storage (Santerre, 1994).

According to the lightness value of the USDA standards for grades of shelled pecans (U.S. Department of Agriculture, 1969) measured by Forbus Jr. et al. (1983), the range of changes in lightness observed in our study could change the grade of pecan

half-kernels from ‘Medium brown’ to ‘Dark brown’ (Table 2). ‘Pawnee’ kernels that were early harvested (Direct) and shelled shortly after harvest resulted in higher lightness values compared to kernels from nuts harvested later (Cluster) or left on the ground for 3 weeks (Ground) in both shelling dates. Other research reports indicated that pecan kernels harvested early have lighter color, while those exposed to delayed harvest are darker (Heaton et al., 1975). Kernel darkening begins around shuck split and continues throughout the harvest period. Pecans that are harvested quickly after shuck split, promptly dried, and refrigerated provide better-quality color and flavor stability than those harvested later because nuts are less exposed to severe weathering conditions such as cycles of drying and re-wetting (Heaton et al., 1975). The change in lightness may be attributed to the change in the amount of tannins leached from pecan shells before the shelling process (Heaton et al., 1975). Moreover, exposure of the kernels to adverse conditions can trigger the plant’s metabolism to synthesize enzymes, phenolic compounds and condensed tannins, which act in oxidative processes (Balasundram et al., 2006; Shahidi and Naczk, 2004).

Table 1. Lightness value of 'Pawnee' half-kernels from 'Direct', 'Cluster', and 'Ground' locations treated with four post-harvest treatments ('AR', 'AA', 'OR', and 'OA') of two shelling dates.

Shelling date	Post-harvest treatment	Location		
		Direct	Cluster	Ground
1st	AR	27.9 a[z]	26.3 abcde	26.0 bcdef
	AA	27.6 ab	26.3 abcde	26.4 abcd
	OR	27.2 abc	25.5 cdef	24.5 defg
	OA	26.5 abcd	26.4 abcde	25.2 defg
2nd	AR	25.9 cdef	26.6 abcd	24.7 efghi
	AA	25.1 defg	25.1 defg	23.3 hi
	OR	25.5 cdef	25.0 defgh	23.3 i
	OA	25.4 def	24.9 defghi	23.6 ghi

[z] Values followed by the same letter are not significantly different from each other (Tukey's HSD 0.05).

Each value is the mean of 24 half-kernels obtained from three-way interaction of shelling date × post-harvest treatment × location.

Table 2. Color attributes reported by Forbus Jr. et al. (1983) for plastic pecan half models used in USDA standards (U.S. Department of Agriculture, 1969) for grades of shelled pecans.

USDA Standard	Color	Hunter color value		
		Lightness	Hue	Chroma
Light	Golden	32.3	51.1	19.4
Light amber	Light brown	31.1	48.6	16.9
Amber	Medium brown	24.4	38.9	15.9
Dark amber	Dark brown	18.0	30.7	6.9

The hue angle is calculated as the ratio of yellowness (b) to redness (a) through this equation (Mcguire, 1992):

$$hue = tan^{-1}\left(\frac{b}{a}\right)$$

The hue value significantly responded to the interaction of location, post-harvest, and shelling date treatments. Based on the USDA grading standard for shelled pecans (U.S. Department of Agriculture, 1969), half-kernel color ranged from 'Golden' (hue = 56.6) in 'Direct', 'AA' in the 1st shelling date to 'Medium brown' (hue = 46.7) in 'Ground', 'OA' in the 2nd shelling date (Table 3). These results suggest that the color of 'Pawnee' half-kernels tends to be in the 'Golden' category if early harvested, shelled and not exposed to heat over 80 °C. Half-kernels from 'Direct' location tend to have greater hue values in most post-harvest treatments in both shelling dates, although most of the differences were not significant. However, differences between the three locations were greater in the 2nd shelling date for the corresponding post-harvest treatments. For the same shelling date, minimum hue values (49.9, 48.0 and 46.7) were associated with 'OA' treatment within 'Direct', 'Cluster', and 'Ground' locations, respectively. Although all hue values in 'Direct' location were greater than those in 'Cluster' and 'Ground' locations for the same shelling date and post-harvest treatments, it is obvious that 'AR' and 'AA' treatments were significantly greater in most locations and shelling dates. Hue values in the 1st shelling date were greater for all post-harvest treatments and locations compared to corresponding treatments in the 2nd shelling date, although differences were not significant in some cases. The combined effect of fast drying ('OR' or 'OA') and time of storage (2nd shelling date) was to increase the intensity of the

brown color. Neither ‘Cluster’ and ‘Ground’ location treatments affected the hue value significantly in the post-harvest treatments within the same shelling date.

Nuts of ‘Ground’ location stayed on the ground of the orchard for three weeks and then stored for 11 weeks. On the orchard floor, these nuts were subject to various weathering conditions such as greater solar radiation, fluctuating temperature, rainfall, and likely higher air and soil humidity.

These results are consistent with the findings of Grauke et al. (1998) and Villarreal-Lozoya et al. (2009) who reported that kernel color changes over time from yellow (higher hue value) to red (lower hue value). The findings are also consistent with the observation of Senter et al. (1984) who reported that the hue value decreased with increasing storage time and temperature. In general, half-kernels that are more golden color than brown have a greater lightness (Table 1) and hue value (Table 2).

Table 3. Hue value of 'Pawnee' half-kernels from 'Direct', 'Cluster', and 'Ground' locations treated with four post-harvest treatments ('AR', 'AA', 'OR', and 'OA') of two shelling dates.

Shelling date	Post-harvest treatment	Location		
		Direct	Cluster	Ground
1st	AR	56.0 ab[z]	53.7 abcdef	53.5 bcdef
	AA	56.6 a	54.1 abcde	54.3 abcd
	OR	53.0 cdef	50. 9 fgh	51.8 defg
	OA	52.5 cdefg	51.4 defg	50.9 fgh
2nd	AR	55.2 abc	51.3 efg	50.9 fgh
	AA	52.3 cdefg	50.0 gh	49.8 gh
	OR	52.6 cdefg	48.3 hi	48.2 hi
	OA	49.9 gh	48.0 hi	46.7 i

[z] Values followed by the same letter are not significantly different from each other (Tukey's HSD 0.05).

Each value is the mean of 24 half-kernels obtained from three-way interaction of shelling date × post-harvest treatment × location.

Chroma, or saturation index, is one of the color attributes that is used in describing the color appearance of foods, along with the other two attributes of lightness and hue (Little, 1975). The Chroma value is derived from yellowness (b) and redness (a) values through this equation (Mcguire, 1992):

$$Chroma = \sqrt{a^2 + b^2}$$

The interaction of location, post-harvest, and shelling date treatments had a significant effect on the Chroma value (Table 4). However, the response was not as clear as it was in lightness (Table 1) and hue (Table 3) values. No specific trend was observed for this effect; however, in the 1st shelling date both 'AR' (13.4) and 'AA' (13.4) treatments were greater than 'OR' (12.7) and 'OA' (12.7) in 'Direct' location. The same response was observed in the 2nd shelling date, although these changes were not statistically significant. Chroma values were greater in most post-harvest treatments in both shelling dates within 'Direct' location compared to corresponding treatments within 'Cluster' and 'Ground' locations. Most Chroma values in 'Direct' location were greater than 'Cluster' and 'Ground' locations for the same post-harvest treatments in both shelling dates. 'Direct' location in the 1st shelling date was greater for all post-harvest treatments than 2nd shelling date, however, most of these differences were not significant. On the contrary, the 2nd shelling date was greater than 1st shelling date in 'Cluster' location for corresponding treatments. The effect of location treatments on Chroma values was more distinct, and data illustrate gradual decrease in the value of Chroma from 'Direct' to 'Ground'. The responses of Chroma values to the location, post-harvest, shelling date treatments and their interactions were significant; however,

this response was erratic and did not correspond to the response of lightness and hue values. Although half-kernel color changed as a response to the studied factors (Fig. 5 and Fig. 6), major color changes were attributed to the changes in lightness (Table 1) and hue values (Table 3), and to a lesser extent, to the Chroma value (Table 4). These findings are consistent with the observations of Grauke et al. (1998) who attributed the change in kernel color mainly to lightness and hue values and very little to Chroma.

The accuracy of visual rating of speckling was tested by comparing the actual reading of the speckled area according to computer software with the area visually estimated with the naked eye. Results in Fig. 7 indicate that there is a strong linear relationship (R^2=0.97) between the two sets of readings. All points were scattered near the trend line, with most of the readings located between 0 and 2%, and, to a lesser extent, between 2 and 7% on the Y axis. These results suggested that most of the half-kernels had low speckling (class 1 = 0-2% speckling), with less with moderate speckling (class 2 = 2-7% speckling), and few with severe speckling (class 3 >7% speckling). The significant linear relationship ($P< 0.01$) between the two readings indicates the strength and reliability of the visual rating scale used in this study.

Table 4. Chroma value of 'Pawnee' half-kernels from 'Direct', 'Cluster', and 'Ground' locations treated with four post-harvest treatments ('AR', 'AA', 'OR', and 'OA') of two shelling date.

Shelling date	Post-harvest treatment	Location		
		Direct	Cluster	Ground
1st	AR	13.4 a[z]	12.2 cdefg	12.0 defg
	AA	13.4 a	11.9 defg	12.3 bcdef
	OR	12.7 abcd	11.7 efgh	11.0 h
	OA	12.7 abcd	11. 8 efgh	12.0 defg
2nd	AR	12.9 abc	13.1 ab	12.6 abcde
	AA	12.7 abcd	12.0 defg	11.3 gh
	OR	12.1cdefg	12.4 bcdef	11.9 defg
	OA	12.5 abcde	11.6 fgh	12.0 defg

[z] Values followed by the same letter are not significantly different from each other (Tukey's HSD 0.05).

Each value is the mean of 24 half-kernels obtained from three-way interaction of shelling date × post-harvest treatment × location.

Post-harvest treatment	Location		
	Direct	Cluster	Ground
AR			
AA			
OR			
OA			

Fig. 5. Color change in representative 'Pawnee' half-kernels from 'Direct', Cluster, and 'Ground' locations treated with four post-harvest treatments ('AR', 'AA', 'OR', and 'OA') of 1st shelling date.

Post-harvest treatment	Location		
	Direct	Cluster	Ground
AR			
AA			
OR			
OA			

Fig. 6. Color change in representative 'Pawnee' half-kernels from 'Direct', Cluster, and 'Ground' locations treated with four post-harvest treatments ('AR', 'AA', 'OR', and 'OA') of 2nd shelling date.

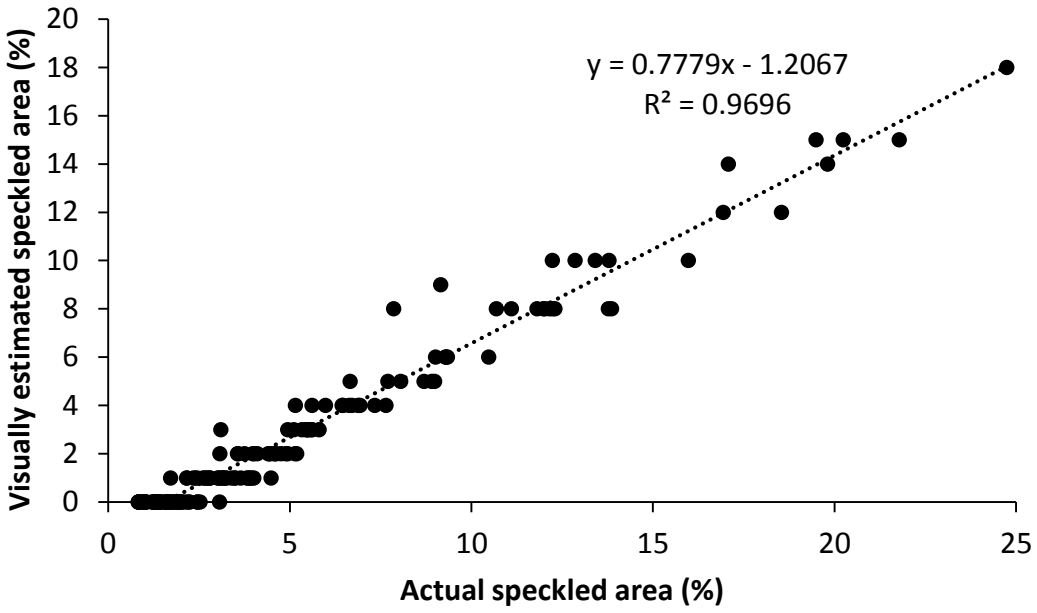

Fig. 7. Relationship between actual (computer reading) and visually (with the naked eye) estimated speckled area on ‘Pawnee’ half-kernels.

Chi Square test at $P \leq 0.05$ showed no significant effect for the 3-way interaction among shelling date, post-harvest, and location treatments on speckling classes. Also, no significant effect was found for the main effects of shelling date and post-harvest treatments and their interaction on speckling classes (Table 5). Data were pooled for the significant effect of location treatment.

Location treatments had a significant effect ($\chi^2 = 9.7$, $P<0.05$) on the speckling rate (Fig. 8). The percentage of class 1 half-kernels was greater (88%) in 'Direct' location and decreased to 85% and 77% in 'Cluster' and 'Ground' locations, respectively. However, an opposite response was observed for class 2 and class 3 speckled half-kernels. Class 2 half-kernels increased from 10% in 'Direct' location to 12% and 18% in 'Cluster' and 'Ground' locations, respectively. Although class 3 half-kernels convey severe speckling and unattractive appearance to consumers, the percentage of half-kernels in this category was at its highest in 'Ground' location (5%). 'Direct' and 'Cluster' locations resulted in 1% and 3%, respectively, class 3 half-kernels. Results indicate that harvest practices has a significant impact on the appearance and percentage of speckling. Pecan nuts from 'Ground' location were subject to different weathering conditions such as fluctuating temperatures and wetness while on the ground for 3 weeks. These environmental effects may have triggered some biochemical reactions and led to the appearance of speckles on kernel testa. To the best of our knowledge, studies on the effect of pre and post-harvest practices on the incidence of speckling are lacking.

Table 5. Chi Square analysis for the effect of location, post-harvest treatments, shelling date, and their interactions on speckling classes (n = 557).

Source	DF	Chi Square	*P*>ChiSq
Location (L)	4	12.825	0.012 *
Post-harvest treatment (T)	6	5.622	0.466
Shelling date (D)	2	0.927	0.069
L × T	22	30.915	0.098
L × D	10	14.959	0.133
T × D	14	9.044	0.828
L × T × D	46	45.776	0.482

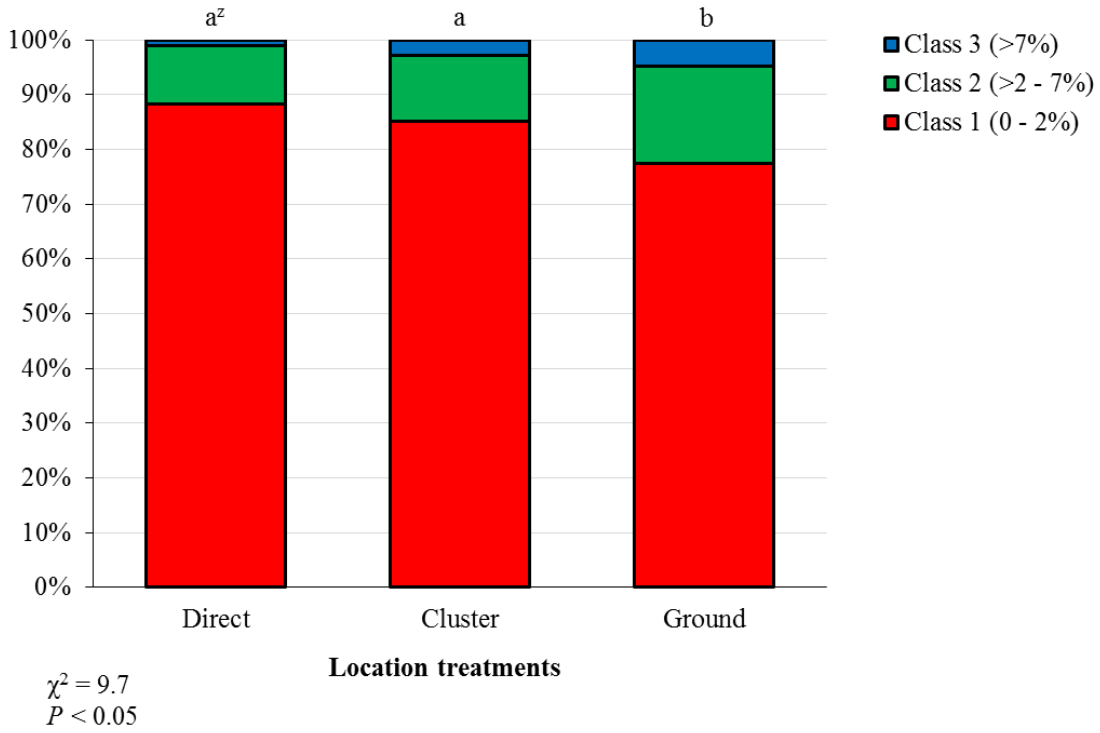

Fig. 8. Effect of location treatment on the percentage of speckling of class 1 (low), class 2 (moderate), and class 3 (severe) on 'Pawnee' half-kernels. Columns with the same letter are not significantly different from each other (Chi Square 0.05).

Experiment 2

Lightness values significantly responded to the interaction among the four post-harvest handling treatments. Values ranged from 26.2 at 0 week at 25 °C of shelled and punctured treatment to 21.1 after 3 weeks in 40 °C of unshelled and not punctured treatment (Table 6). The lightness values decreased over time in all treatments although the reduction was not always significant. The value of lightness decreased more rapidly over time with higher temperature (40 °C) than did values for 25 °C in both shelling and puncturing treatments. The pattern of change in lightness value was similar between the two puncture treatments. No significant effect was detected for the 'Not punctured' treatment in all its interactions as compared to 'Punctured' treatment for the same corresponding interactions. Almost same pattern of response was observed for shelling treatments. No significant effect between shelling treatments for all corresponding treatments except for 3 weeks at 40 °C of 'Not punctured' half-kernels, which was 22.5 and 21.1 for shelled and unshelled treatments, respectively, as well as for 1 week at 40 °C of 'Punctured' half-kernels, which was 25.1 and 23.2 for shelled and unshelled treatments, respectively.

The lightness was at its lowest value after 3 weeks as compared to its initial value; however, this value was significantly lower when associated with 40 °C. These changes in lightness values may be attributed to the degree of tannins polymerization into their condensed forms (Senter et al., 1978; Villarreal-Lozoya et al., 2009). These results are in agreement with Grauke et al. (1998) who suggested that kernel color changed from lighter to darker as a response to time and temperature.

Table 6. Lightness value of 'Pawnee' half-kernels subjected to two puncture and shelling treatments in 25 and 40 °C temperatures over three weeks of storage.

		Not punctured		Punctured	
Shelling	Week	25 °C	40 °C	25 °C	40 °C
Shelled	0	26.0 ab[z]	25.2 abcde	26.2 a	25.4 abcde
	1	25.8 abcd	24.6 defg	25.4 abcde	25.1 abcde
	2	25.5 abcde	23.5 fghi	25.5 abcd	23.5 ghi
	3	25.2 abcde	22.5 ij	24.9 bcde	22.6 ij
Unshelled	0	25.6 abcd	25.0 bcde	25.9 abc	24.9 bcde
	1	25.8 abcd	24.2 efgh	25.2 abcde	23.2 hi
	2	25.3 abcde	22.5 ij	24.8 bcdef	22.6 ij
	3	24.8 cdef	21.1 k	24.7 cdef	21.9 jk

[z] Values followed by the same letter are not significantly different from each other (Tukey's HSD 0.05).

Each value is the mean of 60 half-kernels obtained from four-way interaction of shelling × week × temperature × puncture.

The four post-harvest treatments and their interactions significantly affected the hue value (Table 7). This value decreased over time in all treatments, but this decrease was more rapid at higher temperatures. The highest values were for the 0 week treatment (51.5-52.2) compared to the lowest two values (41.6 and 42.1)) for the 3 weeks, 40 °C, Unshelled treatments. This decline in the hue value changes 'Pawnee' half-kernel classification from golden color (hue ≥ 51.1) to medium brown (hue ≤ 48.6) based on USDA grading standard for shelled pecans (Forbus Jr. et al., 1983). The change in the hue value appeared after 3 weeks of storage at 25 °C except for the 'Not punctured' within 'Shelled' treatment, the effect appeared after 2 week. Same changes in hue values started earlier when stored at 40 °C within 'Shelled' treatment. However, it was not the case for the 'Unshelled' treatment due to the low initial value (48.1) and is already in the medium brown of the USDA classification of shelled pecans. This low initial hue value is probably due to that nuts were stored for 1 week at 40 °C before shelling. The pattern of hue value change was similar between the two puncture treatments. Except for week 1, Shelled, 40 °C treatment, there was no significant effect observed for treatments within 'Not punctured' treatment compared to corresponding treatments within 'Punctured' treatment. Also, the response to the time treatment within 25 °C did not change between the two shelling treatments for corresponding treatments. However, this is not the case for the same treatments at 40 °C. The cause of these changes in hue values can be attributed mainly to the changes in temperature and storage period. It is well known that high temperature storage increases unwanted biochemical reaction (e.g. oxidation) rates. Also, higher temperatures cause relatively quick discoloration in pecan

kernels (Hao et al., 1991). These results confirm the results obtained in Experiment 1 that higher temperature and extended storage periods result in darker and more brown kernels.

Table 7. Hue value of 'Pawnee' half-kernels subjected to two puncture and shelling treatments in 25 and 40 °C temperatures over three weeks of storage.

Shelling	Week	Not punctured		Punctured	
		25 °C	40 °C	25 °C	40 °C
Shelled	0	52.0 a[z]	52.2 a	51.5 ab	52.1 a
	1	51.3 abc	46.4 ijk	51.2 abc	48.1 gh
	2	50.3 bcdef	45.1 klm	51.0 abcde	45.7 jkl
	3	49.7 bef	44.2 lmn	49.9 cdef	43.1 no
Unshelled	0	51.2 abcd	48.1 gh	51.1 abcde	47.2 hi
	1	51.0 abcde	46.7 hij	50.4 bcdef	45.7 ijk
	2	50.5 bcdef	43.8 mn	49.7 ef	43.3 no
	3	49.4 fg	41.6 p	49.4 fg	42.1 op

[z] Values followed by the same letter are not significantly different from each other (Tukey's HSD 0.05).

Each value is the mean of 60 half-kernels obtained from four-way interaction of shelling × week × temperature × puncture.

Chroma value significantly responded to the interactions among the four post-harvest treatments (Table 8). Chroma value gradually decreased over time in all treatments within 'Shelled' treatment, and this decrease was more rapid at 40 °C. However, this pattern of color saturation loss over time was erratic within 'Unshelled' treatment. The highest value (13.2) was for the 0 week, 40 °C, Shelled, 'Punctured' treatment compared to the lowest value (10.3) for the 2 weeks, 40 °C, Shelled, 'Not punctured' treatment. No significant effect was observed between each of treatments within 'Not punctured' treatment and corresponding treatments within 'Punctured' treatment. However, each of treatments within 25 °C was significantly different compared to corresponding treatments within 40 °C, except for those at 0 week of 'Shelled' treatment, which did not change significantly. The changes in Chroma values did not follow the same pattern of changes in lightness and hue values (Table 6 and Table 7) However, the results of color change in this experiment (Fig. 9 and Fig. 10) were similar those obtained from Experiment 1. These results are consistent with the findings of Grauke et al. (1998) that kernel color was changed over time due to the changes in lightness and hue values and very little to the changes in Chroma.

Table 8. Chroma value of 'Pawnee' half-kernels subjected to two puncture and shelling treatments in 25 and 40 °C temperatures over three weeks of storage.

Shelling	Week	Not punctured		Punctured	
		25 °C	40 °C	25 °C	40 °C
Shelled	0	13.0 ab[z]	13.0 abc	13.0 abc	13.2 a
	1	12.2 def	11.2 hi	12.2 de	11.6 fgh
	2	11.8 defgh	10.3 j	12.4 cd	10.8 ij
	3	11.6 efgh	10.6 j	11.6 fgh	10.7 ij
Unshelled	0	12.0 defg	10.8 ij	12.4 bcd	10.7 ij
	1	11.6 fgh	10.7 ij	11.5 gh	10.4 j
	2	11.6 fgh	10.6 ij	11.6 fgh	10.5 j
	3	11.8 defg	10.7 ij	11.8 defgh	10.6 ij

[z] Values followed by the same letter are not significantly different from each other (Tukey's HSD 0.05).

Each value is the mean of 60 half-kernels obtained from four-way interaction of shelling × week × temperature × puncture.

Fig. 9. Color changes of representative shelled ‘Pawnee’ half-kernels subjected to two puncture treatments in 25 and 40 °C temperatures over three weeks of storage.

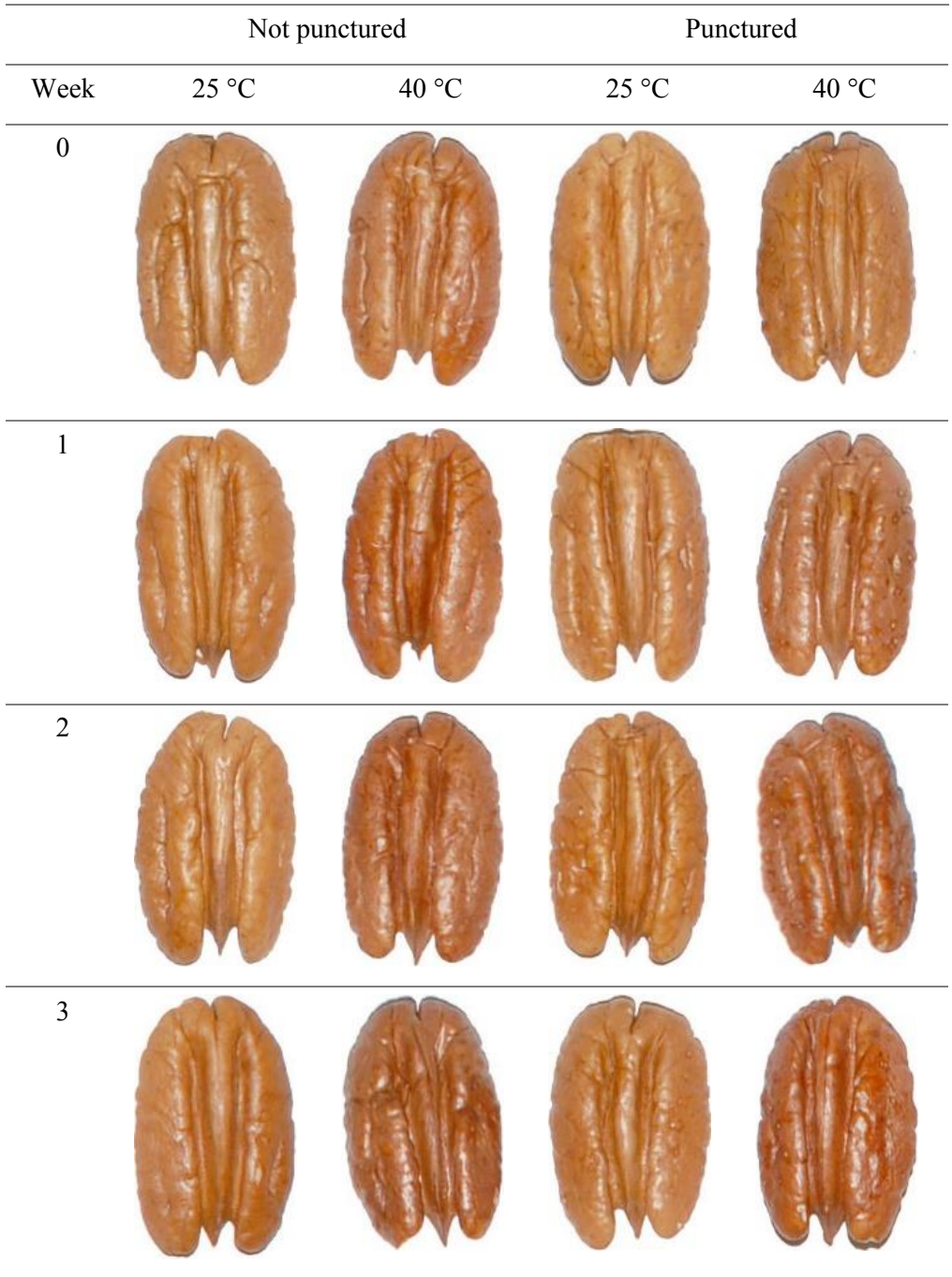

Fig. 10. Color changes of representative unshelled ‘Pawnee’ half kernels subjected to two puncture treatments at 25 and 40 °C temperatures over three weeks of storage.

The color attributes we obtained for each USDA grade from 'Pawnee' half-kernels (Table 9) were different from those obtained by Forbus Jr. et al. (1983) on the USDA half models for each grade (Table 2). From all previous results, it is clear that there is a need to revise USDA Standards for grading shelled pecans, and to find ranges for color attributes to cover all commercial pecan cultivars.

Chi Square test at $P \leq 0.05$ revealed no significant effect for the four-way interaction among shelling, puncturing, storage time, and temperature treatments on speckling classes Also, no significant effect was found for the main effects of shelling and puncturing treatments and their interactions on speckling classes (Table 10). Data were pooled for the significant effect of temperature and storage time treatments. The interaction between temperature and time of storage significantly ($\chi^2 = 26.63$, $P<0.05$) affected the speckling rate of 'Pawnee' half-kernels (Fig. 11). There was a clear trend of decrease in the percentage of class 1 half-kernels over the time within each storage temperature. Greater percentage (71%) of class 1 half-kernels were reported from 25 °C and 0 week treatment and decreased to 61% after 3 weeks in the same temperature. However, initial percentage of class 1 half-kernels (66%) associated with 40 °C decreased to 64% after 3 weeks of storage at the same temperature. The same trend was observed for class 2 half-kernels within 40 °C only. The percentage of class 2 half-kernels decreased gradually from 31% in the 40 °C and 0 week treatment to 25% after 3 weeks in the same temperature. In contrast, the percentage of class 3 half-kernels responded adversely compared to the response of class 1 in the same times and temperatures.

Table 9. Color attributes of 'Pawnee' pecan half-kernels measured in the present study and corresponding USDA standard grade colors of shelled pecan (U.S. Department of Agriculture, 1969).

USDA Standard [z]	Color		Hunter color value		
			Lightness	Hue	Chroma
Light	Golden		27.9	56.0	13.4
Light amber	Light brown		25.9	55.2	12.9
Amber	Medium brown		24.6	46.4	11.2
Dark amber	Dark brown		21.1	41.6	10.7

The initial percentage progressively increased from 3% to 8% after 3 weeks at 25 °C. This increase was more rapid at 40 °C, with the percentage of class 3 half-kernels increasing from 3% to 8% for 0 and 3 weeks, respectively. These results reflect the relationship between the severity of speckling and the time of storage and temperature. Also, post-harvest handling practices may have had a role in initiating or enhancing some physiological processes or biochemical reactions which led to the appearance of speckles on kernel testa. To the best of our knowledge, studies on the effect of pre and post-harvest handling practices (i.e., storage time and temperature) on the incidence of speckling are lacking.

Table 10. Chi Square analysis for the effect of shelling, temperature, puncturing, storage time treatments, and their interaction on speckling classes (n = 1826).

Source	DF	Chi Square	*P*>ChiSq
Shelling (S)	2	0.844	0.656
Temperature (T)	2	6.289	0.043 *
Puncture (P)	2	0.007	0.997
Week (W)	6	14.136	0.028 *
S × T	6	7.263	0.297
S × P	6	2.376	0.882
S × W	14	18.648	0.179
T × P	6	6.383	0.382
T × W	14	25.458	0.030 *
P × W	14	14.887	0.386
S × T × P	14	8.972	0.833
S × T × W	30	31.825	0.376
T × P × W	30	27.405	0.602
S × T × P × W	62	38.128	0.993

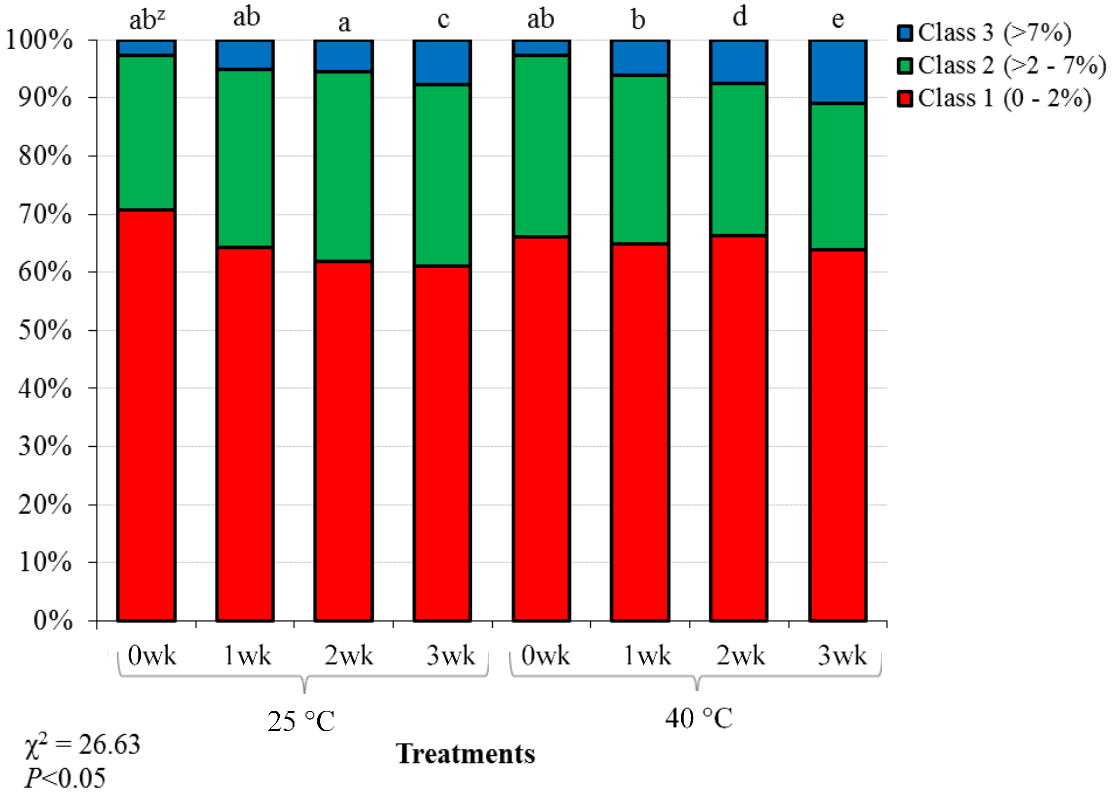

Fig. 11. Effect of storage time and temperature on the percentage of speckling of class 1 (low), class 2 (moderate), and class 3 (severe) on 'Pawnee' kernels. Columns with the same letter are not significantly different from each other (ChiSquare 0.05).

CHAPTER IV

CONCLUSIONS

‘Pawnee’ kernels are characterized by the development of dark spots (speckles) on the testa which aesthetically affect the appeal of the kernels to consumers (Sparks, 2014). The first experiment of this study demonstrated that ‘Pawnee’ half-kernels of ‘Direct’ and ‘AR’ treatments in the first shelling date were lighter and had greater color saturation with less class 2 and 3 speckling. ‘Ground’ and ‘OA’ treatments in the second shelling date were darker with greater number of half-kernels with dark spots. This suggests that early harvested, slow dried, and then refrigerated, pecans maintain quality color half-kernels for 11 weeks, and have reduced speckling.

Based on the results of the second experiment of this research, we can conclude that post-harvest handling treatments (puncture, temperature, shelling, and storage time) significantly affect color quality and speckling appearance of ‘Pawnee’ half-kernels. Better color was obtained from 0 week of storage within shelled pecan treatments which had greater values of lightness, hue, and Chroma. On other hand, these three-color attributes were lower in the 3 weeks, unshelled, and 40 °C treatments, referring to darkness of kernels. Time and temperature treatments were observed to have a greater effect on enhancing the unattractive speckling on ‘Pawnee’ kernel testa. Kernels from the class 2 and class 3 visual rating scale increased with extended storage time and higher temperature conditions.

It is recommended for future studies, to investigate the physiological and biochemical changes in ‘Pawnee’ kernel testa that are responsible for the appearance of

speckling. By understanding the cause behind speckling, ‘Pawnee’ growers will have the chance to plan for better pre and post-harvest processes to enhance the suitability of ‘Pawnee’ kernels in the gift pack trade.

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