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CHANGES IN THERMAL PROPERTIES DURING THE GROWING SEASON TO PREDICT THE APPLE HARVEST TIME AND MONITOR THE QUALITY

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ABSTRACT

Apple is one of the most widely cultivated fruit worldwide and processed into many products. The maturity of apple fruit at harvest is a factor that significantly impacts quality and storage. An early or late picked apple is more sensitive to physiological disorders and has shorter storage life than fruit harvested at the proper maturity time. To determine the harvest time, many physical, biochemical, and physiological properties have been assessed by destructive and nondestructive methods. However, no study on the measurement of thermal properties, which are a set of physical properties to predict the apple harvest time has been reported in the literature. Therefore, the objective of this study was to measure thermal properties, i.e., thermal conductivity, thermal diffusivity, and specific heat, of ‘Gala’ apple cultivar from the Fruit Research and Extension Center, Biglerville, PA during the 2017 growing season using the dual needle heated probe (DNHP), which is simple, rapid, and portable method.

The measured weekly average of thermal conductivity, thermal diffusivity, and specific heat values of apple samples during the growing season in the laboratory (18-23°C) were between 0.441 ± 0.015 and 0.445 ± 0.014 W/m-K, 0.137 ± 0.004 and 0.152 ± 0.006 mm^2/s, and 3.93 ± 0.20 and 4.23 ± 0.25 kJ/kg-K, respectively, with mean temperature of apple from 19.1 to 22.6°C. Average thermal conductivity and thermal diffusivity values of apple decreased significantly as apple ripened ($p < 0.05$) while specific heat values did not change significantly ($p > 0.05$) during the growing season. Overall, the most noticeable changes in thermal conductivity occurred during the last two weeks of the growing season, which corresponds to the time when major biochemical changes are known to occur.

Subsequently, the apple’s thermal property changes during the growing season were examined for their prospective relationships with physical properties (size, density, and moisture content) and harvest fruit quality and maturity indices (firmness, soluble solid content, starch index, and Streif Index). Based on the Pearson correlation coefficient (r) among thermal properties and the physical properties and the harvest fruit quality and maturity indices, thermal conductivity had moderate correlation with thermal diffusivity (0.44), moisture content (0.45), firmness (0.44), soluble solid content (-0.62), starch index (-0.53), flesh stain % (0.44), and Streif Index (0.46) during the growing season. Hence, thermal conductivity can detect the quality changes during the growing season and determine the harvest time of apple but not as the sole predictor.

Keywords: thermal conductivity; DNHP; *Malus x domestica (Borkh.)*; fruit maturity; harvest time

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CHAPTER 1

INTRODUCTION

Apple is one of the most widely cultivated fruit all over the world, which is grown in temperate regions and some tropical areas. The major apple-producing countries are China, the USA, Germany, France, Italy, Turkey, and Iran (Salunke,1995). In the USA, the top five apple fruit producing states are Washington, New York, Michigan, Pennsylvania, and California. According to USDA-ERS records, Pennsylvania produced approximately 5% of 4,183.5 million kilograms (9,223.0 million pounds) of apple in the USA in 2010 (USDA-ERS, 2010). Apple is considered having moderate energy value from its composition: carbohydrate, organic acids, phenolic compounds, and variety of minerals and vitamins. Apples are also processed into various products such as juice, sauce, concentrate, vinegar, wine, cider, butter, candy, jam, and canned, frozen and dried products. These products' quality depends on the quality of fresh apple, which, in turn, depends on the stage of fruit development, cultivar, climate and cultural practices. Harvesting time from late August through October, depending on the apple cultivars, plays a significant role in apple quality. The fruit maturity is mostly related to texture, firmness, skin color, volatiles, and chemical composition (Salunke,1995).

The storage life of apples is also important for the apple quality, which can vary depending on cultivar, production area, cultural practices, climatic conditions, maturity, handling, and transportation. Particularly, harvest timing of apples significantly affects fruits' quality during logistics for immediate consumption or storage. Immature apple that is harvested too early is prone to lacking flavor, poor coloring, shriveling, mechanical damage, and storage scald. Overripe apple that is left on trees too long is highly prone to becoming soft, mealy with undesirable flavor soon, and the potential development of watercore, after harvest. Thus, any apple picked either early or late in the growing season is more sensitive to physiological disorders and has shorter storage life than the one harvested at the proper maturity time (Salunke, 1995; Reid, 2002; Scheerlinck et al., 2004; Thompson, 2015, PSU Extension, 2017). Hence, determination of the optimum harvest time is a crucial issue for growers to ensure the high apple quality expected by the consumers.

Various maturity indices have been used to determine the harvest time of apple by measurement of properties. These include (1) fruit firmness, starch index, soluble solid content, titratable acidity, skin and flesh color, seed color (Ingle et al., 2000; Peirs et al., 2001; Peirs et al., 2002; Scheerlinck et al., 2004), (2) respiration rate, ethylene production, volatile compounds of apple during the growing season and/or storage (Vanoli et al., 1995; Song & Bangerth, 1996; Rizzolo et al., 2006). Further, there have been many studies on prediction of the optimal picking date of apple by non-destructive approaches, i.e., (1) Visible and Near Infrared (VIS/NIR) spectroscopy (Peirs et al., 2001; Peirs et al., 2005; Zude et al., 2006), (2) Diffuse Reflectance-Ultraviolet- Visible and Near Infrared (DR-UV-VIS and NIR) spectroscopy (Bertone et al., 2012), (3) hyperspectral backscattering imaging (Peng &Lu, 2008), (4) laser induced backscattering (Quing et al., 2007), (5) electronic nose (Young et al., 1999; Saevels et al., 2003; Pathange et al., 2005), and (6) biospeckle method (Skic et al., 2016). Beside the fruit properties, predictions of fruit development can be based on meteorological conditions and accumulation of heat units (air and soil temperature) during post bloom periods (Perry et al., 1987; Narasimham et al., 1988; Nilsson & Gustavsson, 2006). These destructive and non-destructive methods are time-consuming and expensive despite not being the sole predictor of the harvest time (Ferree & Warrington, 2003; Skic et al., 2016).

The physical properties of fruits and vegetables are an important indicator of their developmental stages as their biological, chemical, microbiological characteristics. In addition, the physical properties provide engineering data useful in the design of machines, processes, and controls to retain a desirable quality of harvested apple (Abbott, 1999; Sahin & Gulum Sumnu, 2006; Mohsenin, 1986). Typical physical properties of apple, i.e., size, shape, density, porosity, surface area, color, texture, and appearance, during the growing season can be used in assessing the fruit maturity and quality (Salunke 1995; Abbot, 1999; Thompsan 2015). Because physical and chemical properties of apple are usually measured with destructive methods or using qualitative techniques, there have been continuing efforts to develop non-destructive or quantitative physical and chemical characterization methods to assess fruit maturity and quality quickly and accurately (Castro-Giraldez et al., 2010; Bertone et al., 2012; Skic et al., 2016).

To date, thermal properties (thermal conductivity, thermal diffusivity, and specific heat), which are one of the significant physical properties, have not been investigated to characterize fruit maturation. Thermal conductivity is a measure of the ability of a material to transfer heat, which increases with moisture contents. Dry porous solids are poor heat conductors since the pores in materials are associated with air instead of water. (Mohsenin, 1980; Sahin & Gulum Sumnu, 2006). Specific heat is defined as the quantity of heat (kJ) needed to increase the temperature of per unit mass (kg) of the material by one degree (°K) at constant pressure or volume process. Thermal diffusivity is the rate at which heat spreads within materials. Thermal diffusivity is also the ratio of thermal conductivity to volumetric heat capacity (Mohsenin, 1980; Sahin & Gulum Sumnu, 2006). In food materials, these thermal properties are significantly influenced by chemical composition, cellular structure and factors affecting the heat flow paths through material such as porosity, shape, size, and density, (Mohsenin, 1980; Fontana et al., 1999; Sahin & Gulum Sumnu, 2006; Rahman et al., 2009;). Chemical composition, density, porosity, color, and firmness of fruit mostly change during the growing season, especially, during maturation and ripening stages (Westwood, 1993: Salunke 1995). Therefore, changes in thermal properties of apple during the growing season could be candidates for determining the quality and harvest time.

Thermal conductivity of food materials is measured by two methods: (1) steady-state method (non-periodic) – when temperature profile in the test material does not change with time, i.e., is steady with time, and (2) unsteady-state method – when temperature profile in the test material is changing with time. The unsteady-state methods are mostly used in agricultural and biological engineering discipline and are more versatile than the steady-state methods. Thermal conductivity probe method is a popular method to measure the thermal conductivity of food material due to its simplicity and speed of measurement (less than two minutes) (Mohsenin, 1980; Wang & Brennan, 1992; Fontana et al., 1999; Sahin & Gulum Sumnu, 2006, Rahman, 2009) among the unsteady-state methods. The probe apparatus consists of a needle-like probe with a built-in heater and thermocouple (or a separate thermocouple). Single needle or dual needle probe inserted into a long hole of the test material as given in Mohsenin (1980) and Rahman (2009). The advantage of dual needle heated probe (DNHP) method developed by Campbell et al. (1999) is to measure simultaneously thermal conductivity, thermal diffusivity, and specific heat of test material (Campbell et al., 1999; Fontana et al., 1999). Therefore, the purpose of this study was to investigate the feasibility of thermal properties (thermal conductivity, thermal diffusivity, and specific heat) of ‘Gala’ apple cultivar grown in Pennsylvania during the 2017 growing season using the DNHP method. Thermal properties are expected to be a rapid and portable alternative to physical properties in determining the optimum harvest time of apples.

CHAPTER 2

LITERATURE REVIEW

2.1 Food Properties

A food property is defined as any observable characteristic and functionality, which controls a set of organoleptic attributes, health-related functions, and properties related to processing and engineering. Food properties are significant for food preservation, processing, storage, marketing, consumption, and even during post-consumption. Thus, food properties are mainly classified in four major classes; 1) physical and physicochemical properties, 2) kinetic properties, 3) sensory properties, and 4) health properties to facilitate the understanding of food properties and measurements leading to better process design and food product characterization (Rahman, 2009).

Physical and physicochemical properties are measured and expressed in physical and physicochemical ways, which are classified as mechanical, thermal, thermodynamic, mass transfer, electromagnetic properties, and physicochemical constants. Mechanical properties are based on food's structure and its behavior once the physical force is applied, such as compressive strength, impact, and shear resistance. The mechanical properties are also classified into rheological, structural, surface, and mass-volume-area-related properties. Thermal properties are relevant to heat transfer in food. Thermodynamic properties are related to attributes referring phase or state changes in food. Mass transfer properties are based on transport of flow of components in food, and electromagnetic properties depend on food's behavior with the interaction of electromagnetic energy (Mohsenin, 1986; Rahman, 2009).

Kinetic properties are mostly characterized as the rate of biological, biochemical, chemical, physicochemical, and physical changes in food and as the rate of growth, reduction, and death of microorganisms in food. Essentially, the kinetic properties are the rates of the changes in foods and mostly are moderated by properties of microorganisms in food (Rahman, 2009).

Sensory properties are related to the human physiological-psychological perception of food attributes and their interactions. The physiological apparatus (fingers, mouth, eyes, taste and aroma receptors, and ears) feel the food properties, and signals are sent to the brain, which interprets a decision about the food's sensory quality; this is the psychological aspect. The sensory properties of food which are textural properties, color and appearance, taste, odor, sound, and tactile properties that are measured subjectively with individuals and/or objectively with instruments. Both subjective and objective methods can make the quality control process easy during processing, preservation, and storage (Rahman, 2009).

Health properties are based on positive and negative effects of food on health. The positive health properties are classified nutritional composition, medical properties, and functional properties, which promote human health and physical well-being. The negative health impact results in intaking unbalanced and excessive diet. Thus, the negative health properties are grouped as toxic at any concentration and toxic above a critical concentration level, and excessive or unbalanced intake (Rahman, 2009).

2.1.1 Thermal Properties

Thermal properties, a well-known group of physical properties, have not been used to determine the fruit and vegetable maturity. Thermal property controls the heat transfer in the material. The heat transfer in biological materials during the production, handling and processing stage occurs solid-liquid interface, solid-gas interface, liquid-liquid interface, and liquid-gas interface. The heat is transferred from one point to another by conduction, convection, and radiation in the presence of temperature difference. Convection is between a solid surface and the adjacent liquid or gas in movement (e.g., the stirring of liquid foods). Radiation is the transfer of heat by electromagnetic waves (e.g., in a microwave oven, infrared heating). Conduction is the transfer of energy between an object that contacts with each other and/or within the material (e.g., heating of food by direct fire through metal containers) (Mohsenin, 1980; Lozano, 2009). In this form of heat transfers from one part of the solid to another occurs under the influence of a temperature gradient so that any relative motion of the particles in the system should be averted. Heat conduction is generally, defined regarding two mechanisms 1) molecular interchange of kinetic energy and 2) electron drift. In the first mechanism, as the molecules of material are heated, molecules are set into motion. which energizes their neighboring molecules through the thickness of the material by the elastic impact. In the second mechanism, free electrons of material that can drift; are free to move around and within the material (metal), thus, free electrons of material are highly associated with heat conduction (Mohsenin, 1980). Therefore, a knowledge of thermal characteristics as thermal conductivity, thermal diffusivity, and specific heat as well as physical characteristics such as density, shape, and size is required to design and predict the process (Mohsenin, 1986).

2.1.1.1 Thermal Conductivity

Thermal conductivity is a measure of the ability of a material to conduct heat and has the units of W/m-K in the SI system (Sahin & Gulum Sumnu, 2006). The rate of conductive heat transfer is predicted by Fourier's law as shown in equation (1).

$$Q = -kA\frac{dT}{dx} \tag{1}$$

In the Fourier's law given in equation (1), Q is the rate of heat flow (J/s), A is the area of heat transfer normal to heat flow (m^2), $\frac{dT}{dx}$ is the temperature gradient along the x-direction, and k is the proportionality constant called thermal conductivity (W/m K). Thermal conductivity value is independent of temperature gradient but varies with temperature. The thermal conductivity can be expressed in a broader temperature range by an empirical equation (2) where a and b are empirical constants (Rahman, 2009).

$$k = a + bT \tag{2}$$

Thermal conductivity of solid engineering materials depends on the material, temperature, and moisture content. However, thermal conductivity of biological materials varies depending on the physical structure, chemical compositions, the state of the substance, and thermal energy transportation through the molecules in material since biological materials are heterogeneous materials with complex structures (Mohsenin, 1980). Figure 1 shows the order of magnitude of thermal conductivity for several materials. For pure metals, the heat conduction mainly depends on the flow of free electrons, while alloys and nonmetallic solids have fewer to no free electrons and, therefore, the heat conduction mostly occurs by lattice vibration. Thus, metals have higher thermal conductivities than alloys and nonmetallic solids. The diamond also has very high thermal conductivity due to its well-organized lattice structure. In addition, thermal conductivities of food materials vary between that of water (k_{water} = 0.614 W/m K at 27°C) and air (k_{air} = 0.026 W/m K at 27°C). Dry porous solids are poor heat conductors since the pores in materials are associated with air instead of water, as shown in Figure 1 (Sahin & Gulum Sumnu, 2006).

Thermal conductivities of foods are mostly dependent on the composition and any factors affecting the heat flow paths through material such as porosity, moisture content, shape, size, homogeneity, and fiber and their orientation. Further, temperature impacts thermal conductivity of biological materials but is smaller than the impact of cellular structure, density, and moisture of a material. Heat conduction in solids is based on the molecular interchange of kinetic energy. However, heat transfer in liquids and gases occur by molecular collisions, since the intermolecular spacing and the motion of the molecules in fluids are much more than in solids. Hence, thermal conductivities of fluids and gases are poorer than those of solids. Thermal conductivities of liquids are generally between those of solids and gases. However, there are some exceptions to the general behavior such as water and glycerin, which are polar or associated liquids exhibit a maximum thermal conductivity (Rahman, 2009; Mohsenin, 1980).

Thermal conductivity of food materials is measured using either the steady state or unsteady state methods. The steady-state method is a time-independent method, the temperature and heat flux distribution within a flat material which is constant at different locations are measured by an electrical heater resistance or an induction oil (Rahman, 2009). Advantages of the method are simplicity in the mathematical processing of the results, ease of control of test conditions, and more accurate in the results. This method also provides the best heat transfer measurements (Mohsenin, 1980).However, measuring heat transfer of food materials takes a long time to reach equilibration, and the method require specific geometry of sample and large sample size (Sahin & Gulum Sumnu, 2006). On the other hand, the unsteady-state methods being time-dependent method are faster and more versatile than the steady-state methods and preferable for extensive experimental measurements due to short test duration and minimization of moisture migration problems (Mohsenin, 1980; Sahin & Gulum Sumnu, 2006).The unsteady-state methods are the thermal conductivity probe method (line source method), Fitch method, transient hot wire method, point heat source method, and the comparative method. The probe method and Fitch method are mostly used to measure the thermal conductivity of agricultural and food materials (Mohsenin, 1980; Sahin & Gulum Sumnu, 2006).

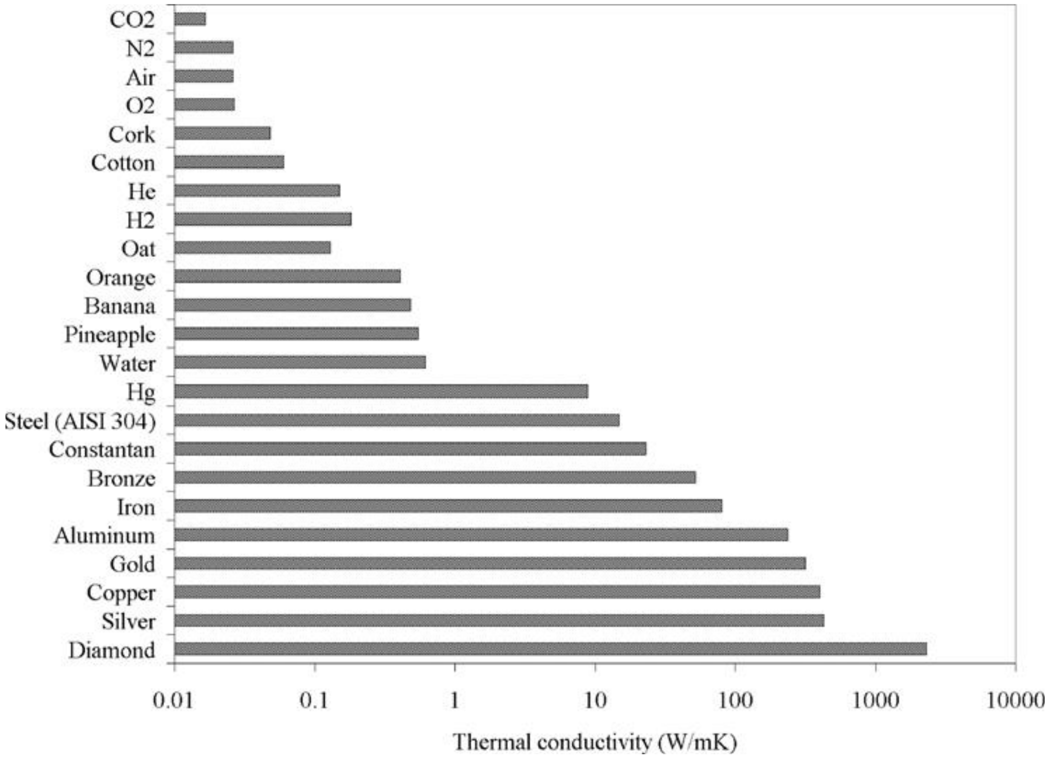


Figure 1 Thermal conductivities of various materials at 27 °C (Sahin & Gulum Sumnu, 2006).

2.1.1.1.1 Thermal Conductivity Probe Method

This is the most popular method to measure thermal conductivity of food materials due to its simplicity and speed of measurement (Sahin & Gulum Sumnu, 2006). A thermal conductivity probe is a narrow circular cylinder of good thermal conductivity, which can be either solid like a needle or hollow with a thick wall (Mohsenin, 1980). The cross-section of the probe and experimental apparatus are shown in Figure 2 and Figure 3, respectively. In this method, a constant heat source is applied to an infinite solid along a line with a very small diameter, such as a thin resistant wire which must have a low resistance (Sahin & Gulum Sumnu, 2006). In measuring thermal conductivity of a material, the probe is either inserted in a long hole of solid foods or at the center of a container filled with small size of the sample such as granular materials (Mohsenin, 1980).

The theory assumes that a line heat source of constant strength is applied in infinite homogeneous and isotropic body at uniform initial temperature. This initial temperature is recorded, and then the probe heater is activated and heated at a constant rate of energy input. Afterward, time versus temperature adjacent to line heat source is recorded (Mohsenin, 1980; Sahin & Gulum Sumnu, 2006). Thermal conductivity is determined only in a radial (r) direction to the probe since axial heat flow is negligible. Thus, the boundary condition can be expressed as shown in equations (3) and (4), where Q is the rate of heat flow (J/s) and k is thermal conductivity. The heat transfer equation for the line heat source method is obtained from the Fourier equation if the temperature (T) versus time (t) data are collected within a specific time interval (t-t_0), where t_0 is the initial or reference time. The heat transfer and the thermal conductivity equations can be expressed as shown in equations (5) and (6), respectively, where ΔT_0 is the initial temperature of the material (Sahin & Gulum Sumnu, 2006).

$$\text{B.C.1 at } r = 0 \ \left(\frac{dT}{dr}\right) = -\frac{Q}{2\pi k} \tag{3}$$

$$\text{B.C.2 at } r = \infty \quad \Delta T\ (r, t) = 0 \tag{4}$$

$$\Delta T - \Delta T_0 = \frac{Q}{4\pi k} \ln\left(\frac{t}{t_0}\right) \tag{5}$$

$$k = \frac{Q}{4\pi} \frac{\ln(t/t_0)}{(\Delta T - \Delta T_0)} \tag{6}$$

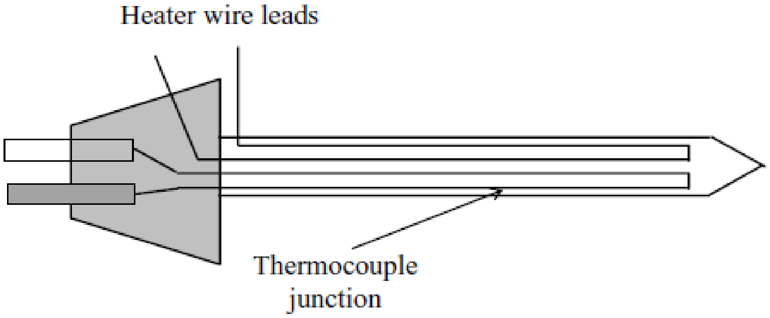


Figure 2 Cross section of thermal conductivity single probe (Sahin & Gulum Sumnu, 2006).

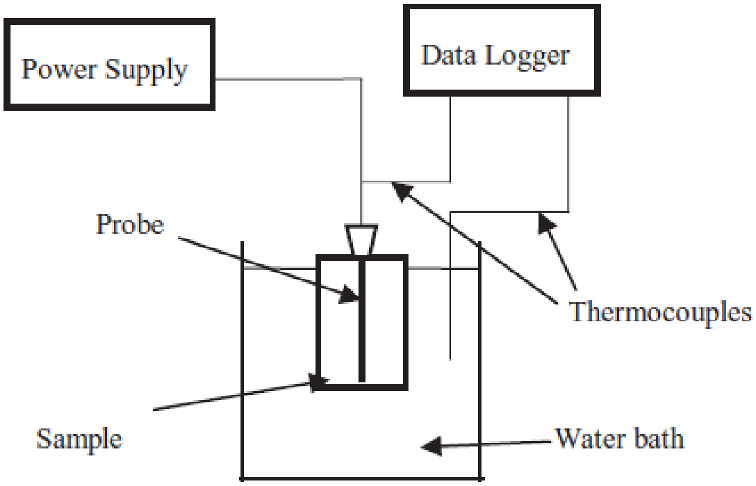


Figure 3 Experimental apparatus for measurement of the thermal conductivity single probe method (Sahin & Gulum Sumnu, 2006).

The probe method has been used extensively to measure the thermal conductivity of some non-food material and food materials. However, this method may not be suitable for thin samples which the probe cannot sufficiently surround the layer of the sample and for liquid due to its density differences that cause disturbing convection currents (Mohsenin, 1980; Sahin & Gulum Sumnu, 2006). However, these disadvantages, especially for liquid, may not be so serious because time is short and the effect of convection currents may be minimal due to the low energy input and short measurement times (Mohsenin, 1980).

There has been demand for precise, rapid, and cheap measurement of thermal conductivity (k), thermal diffusivity (D) or (α), and specific heat (C_p) of foods. A dual-needle-heat pulse probe was developed by Campbell et al. in 1999, which can measure simultaneously C_p, k, and D. The dual-needle-heat pulse probe device consist of two stainless steel 304 parallel needles spaced 6 mm apart as shown in Figure 4. One needle has a thermocouple, and another needle contains a line heat source (heating wire). A short duration pulse (usually 8 seconds) is applied to the heater and then the temperature of the thermocouple versus time are recorded to simultaneously determine thermal conductivity, thermal diffusivity and volumetric heat capacity of the sample (Fontana et al., 1999).

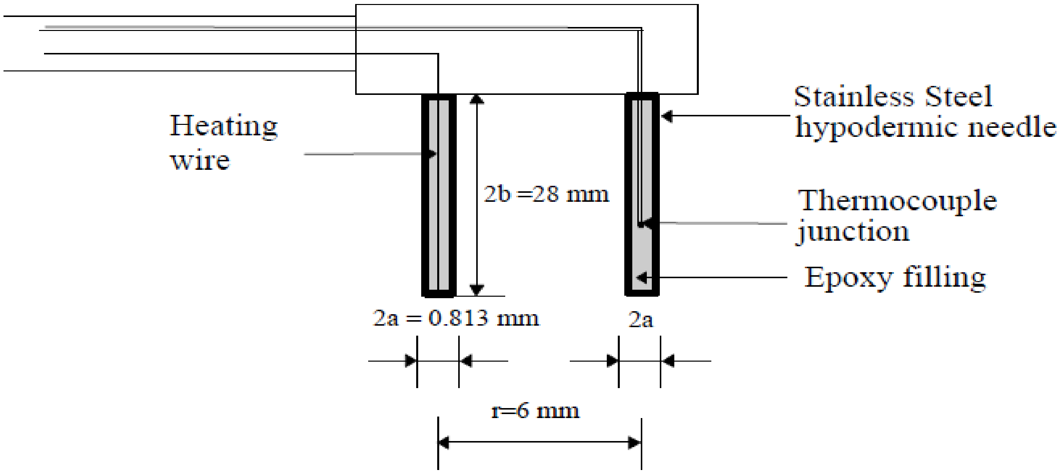


Figure 4 Schematic representation of the dual-needle heat pulse sensor (Fontana et al., 1999).

Thermal conductivity and thermal diffusivity are calculated by using Equation (7) with a mathematical inverse method. In the equation, *r* is the distance between the heating wire and the thermocouple sensor, ΔT is the temperature rise measured by the thermocouple, q is the power dissipated by the heater, k is the thermal conductivity, D is the thermal diffusivity, and t is the time. After thermal conductivity and thermal diffusivity are determined, the volumetric specific heat (C_p) can be calculated by using equation (8) (Fontana et al., 1999).

$$\Delta T = \frac{q}{4\pi kt}\, exp\left(-\frac{r^2}{4Dt}\right) \tag{7}$$

$$C_p = \frac{k}{D} \tag{8}$$

2.1.1.1.2 Fitch Method

Fitch method is one of the most common transient methods used to measure thermal conductivity of materials that are a poor conductor. The Fitch method consists of two parts, “heat source/sink” which consist of a vessel filled with a constant temperature liquid and ‘receiver’ or the sink containing a heat-insulated copper plug as shown in Figure 5 (Mohsenin, 1980; Rahman, 2009). The sample is sandwiched between the vessel and the open face of the copper plug. The method was firstly developed by Fitch in 1935. The Fitch apparatuses were modified to minimize the errors associated with thickness and heat transfer area and to measure thermal conductivity of soft materials such as fruits and vegetables (Bennet et al., 1962), small food particles that can be formed into slabs (Zuritz et al. 1989), and fresh and frozen foods (Rahman, 2009).

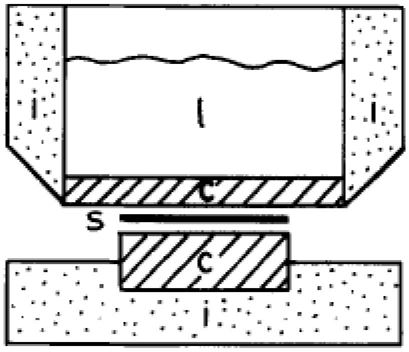


Figure 5 Fitch apparatus, c: copper plug, i: insulation, l: liquid, s: sample (Rahman, 1991).

2.1.1.1.3 Other Methods

In the point heat source method, point heat source is heated for a period followed by monitoring of its temperature as the heat dissipates through the sample. The purpose of a point source is to use for as thermistor which serves both a heating element and a temperature sensor. According to Voudouris & Hayakawa (1994), a theoretical analysis of this method is to determine the lower limits on sample size. The theoretical analysis indicates that the dimensions of the sample should be smaller for the small size of the thermistor. The much smaller thermistor is required for a measurement to compete with the probe method (Sahin & Gulum Sumnu, 2006).

The thermal comparator method is simple, which measures the overall thermal conductivity of sample instead of local measurement; thus, porous foods such as cakes are appropriate for this method. This method involves cooling of two spheres side by side in a well-stirred ice/water bath; one sphere includes a sample, other contains a reference of known thermal conductivity. The thermal conductivity of the sample is determined depending on time-temperature data of the cooling spheres (Sahin & Gulum Sumnu, 2006; Rahman, 2009).

The transient hot-wire method includes a thin heater wire which is located at the interface between the sample and a reference of known thermal conductivity. The hot wire consists of a single wire involving a heater and temperature sensor while the thermal conductivity probe has separate wires for heater and temperature sensor in a tube. In the measurement, once the electrical power is applied to heater wire, the temperature rises at a point located between the two materials are determined, and then thermal conductivity of the sample is calculated. This method is more suitable for measurements under the high pressure than the probe method. Also, this method works best if the thermal diffusivity values of two materials are almost same. Therefore, the reference material for each sample needs to be changed (Sahin & Gulum Sumnu, 2006).

2.1.1.2 Specific Heat

Specific heat is the amount of heat (J) required to raise the temperature of a unit mass (or volume) of the substance by unit degree, (J/kg K or J/m^3 K) in the SI system. The specific heat depends on the nature of the process of heat addition at a constant pressure process or a constant volume process. This is because specific heats of solids and liquids do not depend on pressure much and because pressure changes in agricultural materials and processes are usually small (Mohsenin, 1980). The specific heat of foods can vary depending on their composition so that knowing the specific heat of each component of a mixture or food is usually sufficient to predict specific heat of food or mixture. In 1892, Siebel pointed out that the specific heat of high moisture foods is highly dominated by water content. Thus, the specific heat of food materials cannot be much greater than sum of the specific heat of water and total solid mater. Siebel proposed equations (9) and (10) for an aqueous solution such as vegetable and fruit juices or paste and food materials below freezing point, respectively. In the equations, X_w^w is the mass fraction of moisture within the sample, C_p is specific heat and given kJ/kg K (Sahin & Gulum Sumnu, 2006). The Siebel's equations give a reasonable estimate of specific heat for materials with high water content. Heldman (1975) also suggested an equation (11) to estimate the specific heat of food materials using mass fractions (denoted as X) which are water, protein, fat, carbohydrate, and ash (Sahin & Gulum Sumnu, 2006).

$$C_p = 0.837 + 3.349\, X_w^w \tag{9}$$

$$C_p = 0.837 + 1.256\, X_w^w \tag{10}$$

$$C_p = 4.180\, X_{water}^w + 1.547 X_{prot}^w + 1.672 X_{fat}^w + 1.42 X_{CHO}^w + \; 0.836 X_{ash}^w \tag{11}$$

Experimentally determined specific heat is higher than the predicted value since it may be the presence of bound water and variation of specific heat of the component phases with the source and interaction of the component phase. For this reason, the specific heat of foods and biological materials is directly measured by the method of the mixture, guarded plate, comparison calorimeter, adiabatic agricultural colorimeter, and differential scanning calorimeter (DSC) (Mohsenin, 1980).

The method of mixtures is the most widely used due to its simplicity and accuracy. A known quantity of liquid (typically water) at known initial temperature is mixed with a known mass and temperature of the sample in an insulated container. Then, the equilibrium temperature of the mixture is determined, and specific heat is calculated by using the simple energy balance (12) (Mohsenin, 1980; Sahin & Gulum Sumnu, 2006).

$$\begin{pmatrix}\text{Amount of}\\ \text{the energy given}\end{pmatrix}_{\text{calorimeter}} + \begin{pmatrix}\text{Amount of}\\ \text{the energy given}\end{pmatrix}_{sample} = \begin{pmatrix}Amount\ of\\ energy\ received\end{pmatrix}_{water} \tag{12}$$

The method of the guarded plate is also widely used. In this method, the sample is surrounded by electrically heated thermal guards which are kept at the same temperature as the sample. There is no heat loss since the sample is also being heated electrically. Thus, the electric heat given to the sample at a given time (*t*) is equal to the heat gain by the sample (Mohsenin, 1980).

The comparison calorimeter is used to measure the specific heat of liquids. In this method, there are two cups in calorimeter; one cup is filled with a liquid of known specific heat (typically distilled water) and the other one is filled with the sample liquid. Both cups are heated to the same temperature and placed in the calorimeter to cool down. The temperature data for both liquids are recorded at regular intervals during cooling. Afterward, cooling curves are created for both liquids, and the rates of cooling are measured at the same temperature. Finally, the cooling curves of both liquids are compared, and specific heat of the sample is determined (Mohsenin, 1980).

In the adiabatic calorimeter design, there is neither heat transfer nor mass transfer through the test chamber walls, and the test chamber is enclosed in another chamber to maintain the adiabatic conditions. A measured quantity of heat is added by heating cables placed in the bulk of the material within a container in the test chamber. The heat energy raises the temperature of the material, the container, the chamber walls, any equipment in the chamber. Then, specific heat of sample is calculated by energy balance equation (Mohsenin, 1980; Sahin & Gulum Sumnu, 2006).

Differential scanning method measures the temperature-dependent specific heat and phase transition. In this measurement, the sample is heated at a known and fixed rate, and when the dynamic heating equilibrium of the sample is provided, the heat flow is recorded as a function of temperature. Thus, the heat flow is directly proportional to the specific heat of the sample (Mohsenin, 1980; Sahin & Gulum Sumnu, 2006).

The specific heat of food and agricultural materials can be calculated from other thermal properties such as thermal conductivity and diffusivity by using a constant-temperature heating method and a temperature distribution chart, and the Fourier number (Sahin & Gulum Sumnu, 2006).

2.1.1.3 Thermal Diffusivity

Thermal diffusivity (α) is associated with transient heat flow, and its units are m^2/s in the SI system. It measures the ability of a material to conduct thermal energy relative to stored thermal energy. Materials of high thermal diffusivity quickly change in the thermal environment whereas materials of low thermal diffusivity slowly change, i.e., take a longer time to reach a new equilibrium condition. Accordingly, the ratio of heating times (Δt) of two materials with the same thickness will be inversely proportional to their respective diffusivities as shown in equation (13) (Sahin & Gulum Sumnu, 2006; Rahman, 2009).

$$\frac{\alpha_1}{\alpha_2} = \frac{\Delta t_2}{\Delta t_1} \tag{13}$$

Thermal diffusivity can be determined directly from the measured thermal conductivity, density, and specific heat. Thermal diffusivity is mostly measured by the temperature history method, the thermal conductivity probe method, and the Dickerson method. In the temperature history method in accordance with Heisler (1947), a heating or cooling experiment is performed and then transient temperature history charts are used to determine the thermal diffusivity (Sahin & Gulum Sumnu, 2006). In the Dickerson method (Dickerson,1965) a cylindrical container of radius, *r*, with high thermal conductivity is filled with sample and then placed in a constant-temperature agitated water bath. The container's ends are insulted by rubber corks to provide radial temperature gradient, and the temperatures at the surfaces and center of the cylinder are monitored with thermocouples. The time-temperature data are collected until a constant rate of temperature rise is achieved for both inner and outer thermocouples (Sahin & Gulum Sumnu, 2006; Rahman, 2009).

2.1.2 Thermal Properties of Fruit and Vegetables

A knowledge of the thermal conductivities of fruits and vegetables is necessary for investigations into their preservation, transportation, and processing. They are especially unsuitable for use with the steady state method since evaporation of water from the fruits and vegetable is highly possible due to a long time (at least an hour) required for measurement. The unsteady-state method for measuring thermal conductivities of fruits and vegetables is much more convenient since it possesses the advantages of short test time and suitability for small specimen sizes. The probe method is mostly used to measure thermal conductivity of fruit and vegetable (Liang et al., 1999). Thermal conductivity of many fruits and vegetables are available in the literature as shown in Table 1 and Table 2, respectively, which varies as a function of moisture, temperature, density (Rahman, 2009).

Thermal conductivities of solid fruits and vegetables (orange, apple, banana, and pear and potato, cucumber, tomato, green radish, asparagus lettuce, and carrot) were measured using the probe method and each measurement was completed within two minutes. The water content of fruits and vegetables was found as a dominant factor in determining their thermal conductivities (Liang et al., 1999). Thermal conductivity of apple was determined at various moisture contents and the conductivity decreases with a decrease in moisture content (Lozano et al., 1979; Donsi et al., 1996; Zhang et al., 2011).

The DNHP method was used to measure thermal conductivity, specific heat, and thermal diffusivity of apple, beef, egg yolk, and egg white. This DNHP method provides a rapid, accurate, and economical means for measuring not only thermal conductivity but also thermal diffusivity and specific heat, simultaneously (Fontana et al., 1999). Thermal properties of different fruits and vegetables (orange, lime, onion, okra, pepper, and tomato) were measured at varying temperatures 35°C, 45°C, and 55°C. Thermal conductivity is directly proportional to thermal diffusivity which is indirectly proportional to specific heat. Also, thermal properties (density, moisture, thermal conductivity, thermal diffusivity, specific heat capacity) of the total solid content of fruits and vegetables were low when compared to pure water since they are poor conductors of heat. Thus, the heat energy diffusion or transfer through these fruits during drying, refrigeration, freezing, and evaporation are likely to be slow (Ekpunobi et al., 2014).

Table 1 Thermal conductivity of selected fruits (Rahman, 2009).

Material	MM	X_w	ρ (kg/m^3)	T °C	k (W/m K)	Reference
Apple (green)	PM	0.885	790	27	0.481	Sweat (1974)
Apple (red)	PM	0.849	840	28	0.422	Sweat (1974)
Apple	PM		803	10	0.371	Liang et al. (1999)
Avocado	PM	0.647	1060	28	0.429	Sweat (1974)
Banana	PM	0.757	980	28	0.462	Sweat (1974)
Banana	PM		977	10	0.475	Liang et al. (1999)
Pineapple	PM	0.849	1010	27	0.549	Sweat (1974)
Cantaloupe	PM	0.928	930	28	0.571	Sweat (1974)
Pear	PM	0.868	1000	28	0.595	Sweat (1974)
Pear	PM		993	10	0.543	Liang et al. (1999)
Peach	PM	0.885	930	28	0.581	Sweat (1974)
Peach	PM	0.860	1012		0.580	Phomkong et al. (2006)
Plum (blue)	PM	0.886	1130	26	0.551	Sweat (1974)
Plum	PM	0.675	856		0.540	Phomkong et al. (2006)
Nectarine	PM	0.898	990	28	0.585	Sweat (1974)
Strawberry	PM	0.888	900	28	0.462	Sweat (1974)
Strawberry	PM		530	20	0.520	Delgado et al. (1997)
Strawberry (frozen)	PM			-15	0.935	Delgado et al. (1997)
Orange (peeled)	PM	0.859	1030	28	0.580	Sweat (1974)
Orange	PM		1012	10	0.554	Liang et al. (1999)
Lime (peeled)	PM	0.899	1000	28	0.490	Sweat (1974)
Lemon (peeled)	PM	0.918	930	28	0.525	Sweat (1974)
Grapefruit (peeled)	PM	0.904	950	26	0.549	Sweat (1974)
Papaya	PM	0.877		20	0.575	Kurozawa et al. (2005)

MM: method of measurement, PM: probe method, ρ: density, T: temperature, k: thermal conductivity, and X_w: water content.

Table 2 Thermal conductivity of selected vegetables (Rahman, 2009).

Material	MM	X_w	ρ (kg/m^3)	T °C	k (W/m K)	Reference
Potato	PM	0.835		25	0.563	Gratzek and Toledo (1993)
Potato	PM	0.835		75	0.622	Gratzek and Toledo (1993)
Potato	PM	0.835		105	0.639	Gratzek and Toledo (1993)
Potato	PM	0.835		130	0.641	Gratzek and Toledo (1993)
Potato boiled (2.5 h)	PM	0.851	1064		0.567	Murakami (1997)
Baked potato	PM	0.818			0.556	Murakami (1997)
Asparagus lettuce	PM		1041	10	0.573	Liang et al. (1999)
Butternut	PM	0.877	950	26.1	0.500	Rao et al. (1975)
Boston marrow	PM	0.936	970	23.4	0.533	Rao et al. (1975)
Cucumber (burpee)	PM	0.954	950	28	0.598	Gratzek and Toledo (1993)
Cucumber	PM		994	10	0.568	Liang et al. (1999)
Carrot	PM		950	10	0.530	Liang et al. (1999)
Carrot	PM	0.900	1040	28	0.605	Gratzek and Toledo (1993)
Carrot	PM	0.923		70	0.620	Liang et al. (1999)
Carrot	PM	0.923		130	0.664	Liang et al. (1999)
Beet (red, Detroit)	PM	0.895	1530	28	0.601	Gratzek and Toledo (1993)
Onion	PM	0.873	970	28	0.574	Gratzek and Toledo (1993)
Tomato	PM		901	10	0.4-0.50	Liang et al. (1999)
Cherry tomato	PM	0.923	1010	28	0.462	Gratzek and Toledo (1993)
Turnip	PM	0.898	1000	24	0.563	Gratzek and Toledo (1993)
Spinach (fresh)	PM	0.931	524	21	0.347	Delgado et al. (1997)
Spinach (frozen)	PM			-10	0.366	Delgado et al. (1997)
Sugar beets	PM	0.724	1284	-11	1.038	Tabil et al. (2001)
Sugar beets	PM	0.723	1185	15	0.584	Tabil et al. (2001)
Sugar beets	PM	0.73	1198	30	0.528	Tabil et al. (2001)

MM: method of measurement, PM: probe method, ρ: density, T: temperature, k: thermal conductivity, and X_w: water content.

2.2 Quality Measurement of Fruits and Vegetables

The quality is the standard of something as implied by the degree of excellence of a product or its suitability for use (Abbott, 1999). Quality of product comprises many properties or characteristics that humans construct. Quality of food encompasses sensory properties (appearance, texture, aroma, and taste), nutritive values, chemical compounds, mechanical properties, functional properties, defects, and much more. People use all their sensors to evaluate the quality of a product; sight, smell, taste, touch, and even hearing, so these sensor inputs; appearance, aroma, flavor, hand-feel, mouthfeel, and chewing sounds are the judgment of acceptability of fruits and vegetables. In addition to consumer/human evaluations, instrumental measurements have been designed to predict quality categories and to reduce the quality variations among consumers. That is to say, the purported objective of instrumental measurements are to sufficiently and precisely provide a universal language among researchers and industry for quality assessment (Abbott, 1999). The instrumental measurements have been designed by imitating human testing methods or human perceptions; appearance is detected by measuring electromagnetic (usually optical) properties, texture by mechanical properties, and flavor (taste and aroma) by chemical properties (Mohsenin, 1972; Abbott, 1999). The instruments also can detect sensors based on signals not detectable by humans, which are near infrared, X-ray, magnetic resonance, and electrochemical (Abbott, 1999).

Fruits and vegetables are so variable and quality properties of each one may greatly differ from the average. Sampling and sorting are necessary to predict the average quality and segregate undesirable or outstanding individual fruit and vegetable. Empirical methods have been developed to measure some specific quality attributes, such as to measure ripeness for a classification decision and a mechanism of category (Abbott, 1999). Ripeness or maturity stage evaluation of fruit or vegetable assures that the product attains the optimum eating quality (Mohsenin, 1972).

2.3 Maturation and Maturity Indices

The horticultural maturity development consists of several stages. These are the growth stage during which cell division and cell enlargement occur, the maturation stage in which associated with physiological maturity is attained just prior to beginning of the ripening stage, and the senescence or melting stage as shown in Figure 6 (Westwood, 1993 & Reid, 2002).

Horticultural maturity is also referred as the stage at which growth or development is optimum for a particular use. For instance; 1) harvested physiologically immature fruit and vegetables (green cucumbers, green tomatoes, summer squash, and berries) for brining. In addition, there are different optimum maturity levels for the same cultivars based on desired use. 2) Harvested firm mature but ripened later fruit (peach, apple, pear, and plum), and 3) harvested fruit and vegetables when ripe, such as cherries, nuts, slicing tomatoes, fruits for canning and drying, and fruits for roadside market (Westwood, 1993).

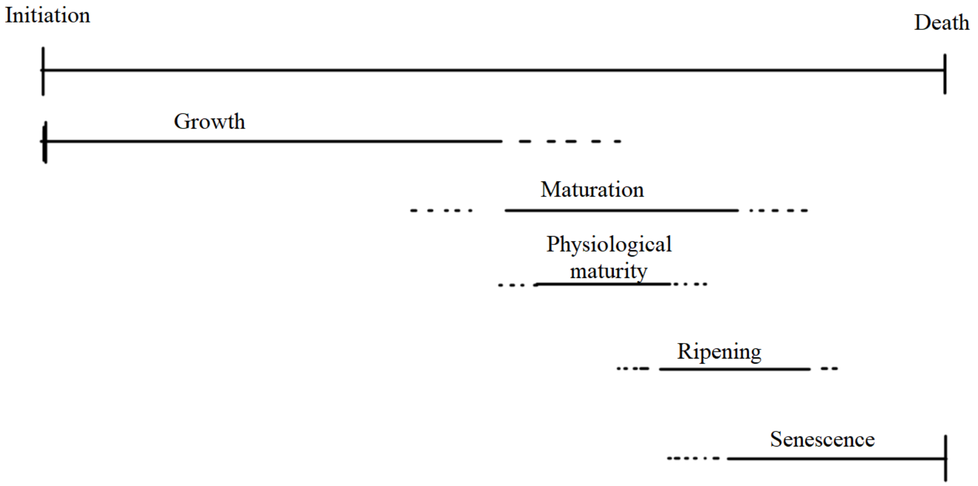


Figure 6 Development stages of fruit (Reid, 2002).

Maturation involves physical, biochemical, and physiological changes during the growing season. The physical and visual changes are altered texture, a decrease of firmness, skin chlorophyll, and an increase of carotenes, xanthophylls (green to yellow), and anthocyanins (red overcolor). The biochemical and physiological changes are a decrease of starch (some fruits), acidity, and air respiratory activity and an increase of sugars, soluble solids, and soluble pectins (Westwood, 1993).

Figure 7 represents an overview of the most relevant metabolic process and changes during the growing season in climacteric fruit. Carbohydrates of climacteric fruit are accumulated in the form of starch in early stage, and they are hydrolyzed into sugars (monosaccharides, mainly glucose and fructose) as the fruit ripens. Starch hydrolysis is a process that requires high energy consumption. It is also related to an increase in fruit respiration rate (climacteric crisis) until reaching the end of ripening (climacteric peak). Eventually, the respiration rate decreases during senescence. Respiration rate of fruit is measured depending on the uptake of oxygen or the output of carbon dioxide, ethylene or other organic volatile compounds linked with ripening. Ethylene production, which is a ripening hormone in climacteric fruit can be a useful indicator of the maturity of the fruit. In general, optimum harvest date is 1-15 days after the initiation of the ethylene rise. In addition, organic acids are strongly related to maturity process in which ethylene is produced from 1-amine-1caboxyl cyclopropane acid; further, the intense respiratory activity consumes malic acid in an oxidative decarboxylation. Thus, the acidity of fruit gradually decreases as fruit matures on the tree and this acidity is usually related to soluble solids. Sugar content in fruit is generally given as a soluble solid since sugars are soluble solids and largest quantity of soluble solids in fruit. Volatile chemicals are also important, and many fruits synthesize aroma compounds giving the fruit a characteristic odor as they ripen. (Janick, 1992; Kader, 1999; Castro-Giraldez et al., 2010; Thompson, 2015)

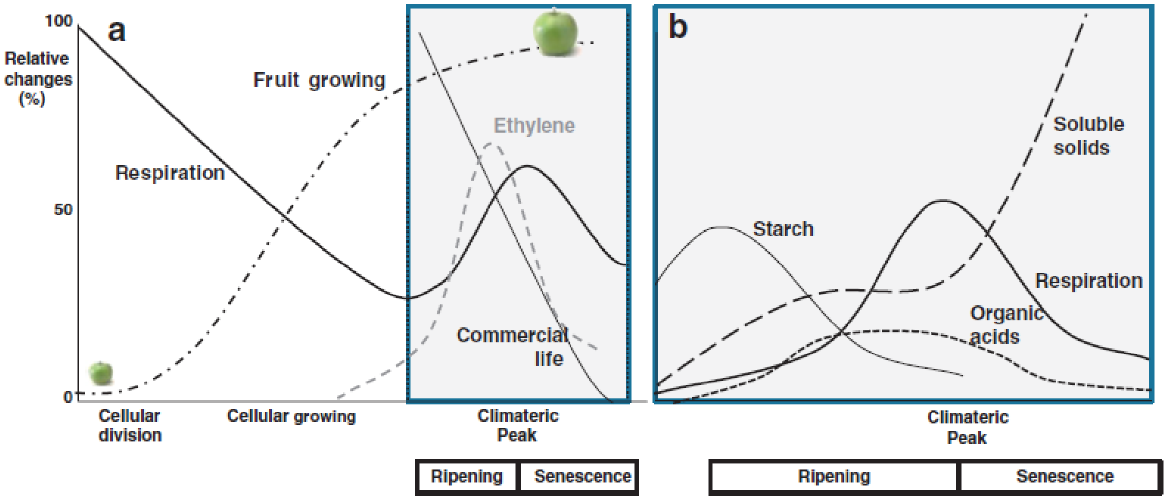


Figure 7 a) Qualitative evolution of respiration rate, fruit growing, ethylene levels, and commercial life of Granny Smith apple; **b)** Qualitative evolution of starch, soluble solids, organic acids content during the ripening and senescence (Castro-Giraldez et al., 2010).

Maturity at harvest is the most important factor which determines final fruit quality and storage-life. Harvesting too early results in immature fruits that are prone to lacking flavor, poorly colored, shriveling, mechanical damage, and storage scald. Leaving fruit on the tree to long results in overripe fruits that are highly prone to becoming soft, mealy with undesirable flavor soon, and the potential development of watercore after harvest. Thus, any fruit picked either early or late in its season is more sensitive to physiological disorders and has shorter storage life than fruit harvested at the proper maturity time (Reid, 2002 & PSU Extension, 2017).

To determine the maturity time, many features of fruits and vegetables have been used. These features are visual and physical properties (such as skin color, size, shape, firmness, tenderness, structure, and density), chemical compositional factors (starch, sugar, acid content, ethylene concentration, and aroma compounds), and computation of time between flowering and fruit being ready for harvesting. A wide range of method has been used to measure these features that are summarized in Table 3 (Reid, 2002). These methods are used to assess the maturity of product that may be used depending on the subjective and/or objective estimates to have more consistent and accurate results. In many of the methods, a qualitative attribute of the crop is used to determine either during preharvest and harvest quality or postharvest quality (Thompson, 2015). Size and shape of the fruit grow during maturation, which can be used as characteristics to determine the harvest time as related to market requirements. Skin color is an important factor to determine the fruit picking time. However, color changes may occur differently depending on the crop, cultivar, growing season, and the position of fruit on the tree (Kader, 1999; Thompson, 2015).

Further, fruit firmness measurement is widely used and mostly determined by destructive methods. Fruit firmness changes during maturation particularly during the ripening stage, in which fruits quickly soften as shown in Figure 8 (Kader, 1999; Brummel, 2006; Thompson, 2015). The fruit of firmness is a function of the cell wall and bonding between neighboring cells and contents of the cells. During the fruit ripening, cell-to-cell bonding weakens with hydrolysis of middle lamella pectin; thus, fruit tissues become soft (De Bellie et al., 2000). These predictors can vary either depending on cultivar or temperature fluctuations within and between seasons.

Table 3 Methods of maturity determination (Reid, 2002).

Index	Method of Determination	Subjective	Objective	Destructive	Non-Destructive
Elapsed days from full bloom	Computation		x		x
Mean heat units	Computation of weather data		x		x
Development of abscission layer	Visual or force of separation	x	x		x
Surface Structure	Visual	x			x
Size	Various measuring devices, weight		x		x
Specific gravity	Density gradient solutions, flotation techniques, vol/wt		x		x
Solidity	Feel, bulk density, gamma rays, X-rays	x	x		x
Textural properties:					
Firmness	Firmness testers, deformation		x	x	
Color, external	Light reflectance		x		x
	Visual color charts	x			x
Color, internal	Light transmittance, delayed light emission		x		x
	Visual examination	x		x	
Compositional factors:					
Dry matter	Sampling, drying		x	x	
Starch content	KI test, other chemical tests		x	x	
Sugar content	Hand refractometer, chemical test		x	x	
Acid content	Titration, chemical tests		x	x	
Juice content	Extraction		x	x	
Oil content	Extraction, chemical test		x	x	
Tannin content	Ferric chloride test		x	x	
Internal ethylene	Gas chromatography		x	x	x

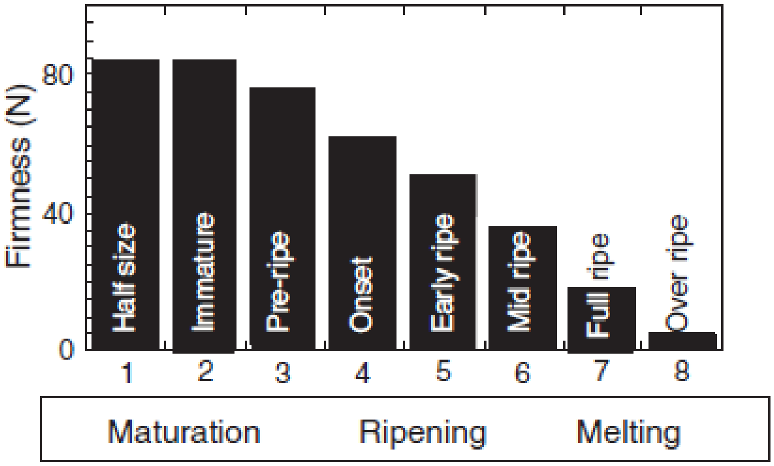


Figure 8 Decline in fruit firmness during maturation and ripening (Brummel, 2006).

2.4 Apple

Apple (*Malus x domestica* Borkh) is highly profitable and popular fruit, which is grown on trees in mostly temperate regions and some tropical areas of the world. The major apple-producing countries are China, the United States, Germany, France, Italy, Turkey, Iran, Argentina, Japan, and India (Salunke,1995). Apple production has been static or declining in many countries. According to USDA-ERS Statistics, in the year 2010, China, the United States, and Turkey represented around 47%, 6%, and 3% of total apples produced 69,567,526 tons in the world respectively. In the USA, apples may be grown in many parts of the country, and the top five apple fruit is producing states are Washington (60%), New York (13%), Michigan (6%), Pennsylvania (5%), and California (3%). Pennsylvania produced approximately 5% of apples produced 4,183.5million kilograms (9,223.0 million pounds) in the USA (USDA-ERS, 2010).

There are over 7,500 cultivars of apple all over the world, but only a few are commercial cultivars. Also, apple cultivars have been changing rapidly, and the new apple cultivars are more resistant to diseases and more productive than established cultivars. Many of the new cultivars are introduced to other countries, and the marketplace may shift due to fruit taste and quality. In the USA, there are over 100 apple varieties grown commercially, and some of the most common varieties are ‘Red Delicious’, ‘McIntosh’, ‘Golden or Yellow Delicious’, ‘Gala’, ‘Granny Smith’, ‘Fuji’, ‘Braeburn’, ‘Pink Lady’, ‘Honeycrisp’, ‘Cameo’, and ‘Empire’ (Janick, 1992; Salunke, 1995; PSU, 2016).

Apples are also processed into several products such as juice, concentrate, cider, wine, vinegar, sauce, butter, candy, jam, jellies, and canned, frozen, and dried products. Besides these, the waste from the apple processing industry which is peel, core and/or pomace can be utilized for production of pectin and several edible products. Apples and their waste products' quality are based on fresh apple quality which, in turn, depends on cultivar, stage of fruit development, growing region, climate, maturity, cultural practices and processing (Salunke, 1995).

2.4.1 Fruit Development and Ripening

The fruit development and ripening stage are complex processes, which involve many physiological and biochemical changes, such as, texture, firmness, color, volatiles, and chemical composition. The changes are usually prior to or accompanied by CO_2 evaluation and ethylene production. Apple is climacteric fruit; once an apple reaches physiological maturity and ripening stage, respiratory activity rises up as a result of the increased evolution of CO_2 (Janick, 1992: Salunke 1995; Ferree & Warrington, 2003). Thus, the rise in respiration rate is minimum at maturity and constant prior to the onset of fruit ripening (Salunke, 1995), and timing of the climacteric and ripening of apple is upgraded by exposure to ethylene (Ferree & Warrington, 2003). However, the effect of ethylene as a ripening factor can be inhibited by increasing carbon dioxide concentration and reducing oxygen in the fruit, since carbon dioxide may compete with ethylene to bind to a receptor during the reaction (Salunke 1995).

The general changes including softening of fruit flesh, hydrolytic conversions of carbohydrate in the fruit, and changes in pigments and flavors are linked with ripening and can be attributed to the energy provided by respiratory activity (Salunke,1995). Total organic acid content gradually declines in fruit during maturation, ripening, and storage. Fruit flavor plays a significant role in consumer acceptance, which results from the combination of sugars, acids, and astringent and aromatic compounds in the fruit. Also, solid concentration incorporates soluble sugars, organic acids, and inorganic salts, some of which increase and/or some decrease during fruit maturation. Sugar content is the major component of soluble solids and prone to increase as apples ripen. This is because starch accumulates at an early stage and is hydrolyzed into sugar during apple maturity. Further, fruit firmness can vary depending on cultivars and seasons. Even though firmness cannot be used as the only indicator of maturity, it is markedly correlated with overall quality and texture, a particularly good indicator for fruit crispness and juiciness. As a fruit develops, the firmness of fruit decreases continuously (Figure 7). In addition, fruit's green skin and flesh color change as chlorophyll is lost during the maturation. As a matter of fact, the rate of chlorophyll production slows and other pigments, particularly, yellow and red appear in the skin once apple maturation begins. The seed color becomes brown and parallels the disappearance of starch as the apple ripens (Janick, 1992).

2.4.2 Chemical Composition of Apple

In the developed apple, the water content and porosity vary from 75 to 90% and 25% of the developed apple, respectively. Carbohydrates, significant food constituents in apple, are starch, sugars (fructose, glucose, and sucrose), the unavailable fractions (pectin cellulose and hemicellulose). Starch, hemicellulose, and dextrin accumulate in apples at a very early stage of its development and gradually decline as apple ripen. Organic acids which are the most important components in apples are primarily malic acid and followed by citric, lactic, and oxalic acid. The total acidity in the fruit considerably contributes to its eating and cooking quality. Fresh apples contain 0.26% ash contents, which may have different minerals coming from different soils in same regions or different regions. Potassium represents a big part of the total mineral contents of apples and is followed by other prevalent minerals: phosphorus and calcium. The significant vitamin content in the apple is vitamin C (ascorbic acid) which is around 5 mg of 100 g of apple. Apples also contain various phenolic compounds involving hydroxycinnamic derivatives, flavanols, anthocyanins, dihydrochalcones, monomeric flavan-3-cells, and tannins. The phenolic compounds are very high in young fruits and rapidly decrease during fruit development stage. The phenolic compounds are involved in enzymatic browning, and the total phenolic content of a ripe apple is ranging from 0.15 to 2.5%. The major phenolic compounds are quinic acid, epicatechin, and quercetin-3O-b-D-galactopyranoside. The chemical composition of apple fruit is summarized in Table 4 (Salunke, 1995).

Table 4 Components of fresh apple fruit (Salunke, 1995).

	Component	Concentration
Proximate (%)	Energy (kcal)	48-59
	Water	83.9
	Protein	0.19
	Lipid	0.36
	Carbohydrate	15.3
	Ash	0.26
	Fiber	0.77
Mineral (ppm)	Potassium	1150
	Phosphorous	70
	Magnesium	50
	Calcium	7
	Chloride	4.26
	Iron	1.8
Fibers (g/100 g)	Total non-cellulosic polysaccharides	6.89
	Cellulose	2.68
	Lignin	0.53
	Dietary fiber excluding resistant starch	10.1

2.4.3 Current Maturity Indices of Apple

Determination of the optimum harvest time plays a key role in the agro-food chain for the fruit quality and appropriate storage conditions during the postharvest period. Many methods have been proposed as indices of apple maturity, which can be divided into (1) destructive and (2) non-destructive methods (Skic et al., 2016).

(1) Destructive methodologies have been traditionally used as reference measurements of fruit quality despite being time-consuming and expensive methods. The destructive methods involve standard physical and chemical analysis based on the evaluation of starch content, soluble

solid content, titratable acidity, measurement of firmness, skin and flesh color, and seed color (Ingle et al., 2000; Peirs et al., 2001; Peirs et al., 2002; Scheerlinck et al., 2004). There is also another maturity index, Streif Index, which is cumulative of firmness, soluble solid concentration, and starch degradation index. The Streif Index declines during fruit development (Streif, 1996). Additionally, the respiration rate, ethylene production, volatile compounds of apple are determinant of optimum harvest date (Vanoli et al., 1995; Song & Bangerth 1996; Rizzolo et al., 2006).

(2) Non-destructive methods are fast, robust, and can be used to carry out continuous measurements on the same samples during different development stages of fruit in the orchard. Various non-destructive systems have been developed. These include optical methods such as Visible/Near infrared (VIS/NIR) spectroscopy, (Peirs et al., 2001; Peirs et al., 2005; Zude et al., 2006), Diffuse Reflectance- Ultraviolet- Visible and Near Infrared (DR-UV-VIS and NIR) spectroscopy (Bertone et al., 2012), hyperspectral backscattering imaging (Peng &Lu, 2008), laser induced backscattering (Quing et al., 2007), electronic nose (Young et al., 1999; Saevels et al., 2003; Pathange et al., 2005), and biospeckle method (Skic et al., 2016). Beside the fruit properties, predictions of fruit development can be based on meteorological conditions and accumulation of heat units (air and soil temperature) during post bloom periods as well (Perry et al., 1987; Narasimham et al., 1988; Nilsson & Gustavsson, 2006).

The most appropriate maturity indices and desirable values for these indices have been established after several season’s evaluations of fruit quality at harvest. Desirable values for maturity indices are specific for each fruit, their cultivars, and use of fruit. Also, the maturity indices are not the sole predictor and are correlated with each other (Ferree & Warrington, 2003). Ingle et al. (2000) tested the fruit characteristic of ‘York’ apples during development regarding soluble solid concentrations, starch index, internal ethylene concentration, and titratable acid concentration. Firmness is positively correlated with titratable acidity while and soluble solid concentration is negatively correlated with starch index which, in turn, is negatively correlated with titratable acidity. Hoehn et al. (2003) tested efficacy of instrumental measurements for determination of minimum requirements of firmness, soluble solid content, and acidity of several apple varieties in comparison to consumer expectations. Consumer acceptance of apple (‘Gala’ and ‘Elstar’) seemed less dependent on firmness, soluble solid content, and acidity, but dependent on aroma quality and juiciness. Rizzolo et al. (2006) evaluated the influence of harvest date on ripening and volatile compounds in the Golden Orange apple. They found that the volatile compounds and their concentrations are much more dependent on harvest date and the length of post-harvest ripening stage than firmness, soluble solid content, titratable acidity, starch hydrolysis and Streif Index. Also, Song & Bangerth (1996) indicated that volatile compound production was highly maturity-dependent and closely related to changes in respiratory rate and ethylene production. They pointed out that respiration rate and ethylene production is lower in earlier-harvested fruit so that aroma synthesis may be limited.

Further, the effect of fruit position within the canopy on the onset of respiratory climacteric and the rise in ethylene production as well as changes in peel color and chemical composition were tested in apples for 6-8 weeks in normal air at 20°C during ripening period over two crop seasons. In the beginning, the rise in both CO_2 and ethylene production was equal independent of fruit position; however, the peak of ethylene was behind that of CO_2 with a lag of several days. During maturation, the fruit on the tree which is positioned outside developed red peel color while the fruit on the tree that is positioned inside remained green. Also, the fruit positioned outside had a higher content of dry matter, soluble solids and sugars, and lower amount of titratable acidity than the fruit positioned inside of the tree. The second year had higher summer temperatures than the first year. High summer temperatures in the second year resulted in a significantly higher content of soluble solids and organic acids (malic and citric acid) independent of fruit position. However, the soluble solids difference and the difference in malic acid and citric acid concentration between the fruits positioned outside and inside on tree decreased and increased, respectively. High summer temperatures also increased the difference in peel color between outside and inside fruit. The difference seems to be strongly dependent on the growing conditions and season (Nilsson & Gustavsson, 2006). In addition, apple maturation is governed by meteorological conditions (temperature, precipitation during the pre-bloom period and the first half of the post-bloom period). The meteorological factors have significant correlations with the actual optimum harvest period determined using physiological factors (starch pattern index and seed, and color index) (Narasimham et al., 1987). Another method used to predict harvest date of apple was heated unit accumulation. The methods of calculating the heat units of a number of days from full bloom (30, 40, 50, and 60 days post-bloom periods) were applied to air temperature during for consecutive years. This method was not a good predictor because of the large number of years of data needed to improve its accuracy (Perry et al., 1987).

Recently, the focus has been on developing sensors for real-time, non-destructive sorting (Abbott, 1999). Destructive techniques suffer from several drawbacks (time consuming and expensive) which reveal the need for non-destructive tools to determine ripeness stage. UV-VIS analysis has been used for characterization of each fruit ripening stage on trees. With this analysis, variations in the chlorophyll content of red skinned apples can be determined, since the color is a valid tool to identify ripening (Bertone et al., 2012). VIS/NIR spectrometer has been applied on apple fruit to predict flesh firmness, starch index, acidity and soluble solid content which are a good indicator of maturity.

The non-destructive sensors for predicting accepted fruit parameters enable the determination of optimum harvest date (Peirs et al., 2000; Zude et al., 2005). A thermal camera was used to capture the images of apple trees during vegetation period June-September. The images were recorded late in the afternoon to achieve temperature gradient between fruits and their background. According to fruit development and the established growing curve, fruit's size and color slightly increased during ripening period (Stajnko et al., 2002). According to Peng & Lu (2007), hyperspectral scattering is a promising technique for nondestructive sensing of multiple quality attributes of apple fruit. They evaluated and compared different mathematical models for describing the hyperspectral scattering profiles over the spectral region between 450 nm and 1000 nm to select an optimal model for predicting fruit firmness and soluble solids content (SSC) of 'Golden Delicious' apple. They found that the wavebands around 675 nm had the most significant impact on predictions of the firmness and SSC compared to other wavelengths. Also, they stated that chlorophyll content played a significant important role in influencing firmness and SSC. As the chlorophyll content decreases, both firmness and SSC in fruit changes.

Hence, fruit SSC could be indirectly related to the change in its chlorophyll content. Skic et al., (2016) studied on biospeckle activity (BA) in relation to standard quality attributes (firmness, acidity, starch, soluble solids content, Streif Index) and physiological parameters (respiration and ethylene emission) of two type of apple cultivars. Changes in BA have moderate relationships with biochemical changes during apple maturation and ripening period. Also, a characteristic decrease in BA matched with Streif Index suggesting harvest date and postharvest quality indicators. The ability of biospeckle method was confirmed by significant correlations with firmness, starch index, total soluble solids, Sterif Index, and changes in carbon dioxide and ethylene emission to characterize the biological state of apples. However, the BA method cannot be solely used to predict the harvest time (Skic et al., 2016). Changes in aroma of apple harvested at four different maturities were measured at harvest and after short-term storage using electronic nose and gas chromatography methods. The electronic nose was found to be more sensitive and less complex than gas chromatography in terms of sample size and sampling procedure, respectively. The electronic nose was found as potential maturity indicator by characterizing apple aroma compounds such as overall flavor, acid flavor, crispness, vegetative aroma (Young et al., 1999). The electronic nose emits the natural gasses accumulated in the ripening fruit stage. Electronic nose sensor data indicated that there were different maturity groups (immature, mature and over-mature fruits) (Pathange et al., 2005). The volatiles of apples ('Jonagold' and 'Braeburn') were assessed during the growing season by means of an electronic nose. The prediction of maturity is compared with Streif Index and showed a cross-validation correlation of 0.89 and 0.92 for 'Jonagold' and 'Braeburn' fruit, respectively (Saevels et al., 2003).

2.5 The State-of-Art of Prediction of Apple Harvest Time with Their Thermal Properties

Thermal properties are one of the significant properties among physical and physicochemical properties, which represent a material's ability to conduct, store, and lose heat in materials. Thermal conductivity, specific heat, and thermal diffusivity are associated with heat transfer, which are mostly dependent on water content, porosity (void fraction), shape, size, homogeneity, fiber and their orientation. Thermal properties of fruit are important for process design and food product characterization.

Apple is one of the most widely cultivated fruit all over the world. Apple is food of moderate energy value due to carbohydrate, organic acids, phenolic compounds, and several minerals and vitamins. Apple quality depends on cultivar, production area, cultural practices, climatic conditions, maturity, handling, and transportation. Particularly, the harvest time of fruit is a significant factor that impacts quality and shelf life. The fruit maturity is related to physical properties (texture, firmness, skin color), volatiles and chemical composition, and respiration rate and ethylene production during the fruit development and ripening. There are many studies on destructive and non-destructive methods to predict the apple harvest time as summarized in preceding sections.

There have been continuing efforts for improving the accuracy of current methods and develop new, quicker, and more accurate methods to find a better prediction method and/or model because most of the current methods are time-consuming and/or expensive. Since the measurement of thermal properties takes less than two minutes and the probe method is relatively inexpensive, therefore, it is proposed as a candidate for measurement of thermal properties. In addition, there has been no study on measurement of thermal properties during a growing season for apples and its use for predicting the harvest time. Accordingly, the goal of this study was to investigate thermal properties (thermal conductivity, thermal diffusivity, and volumetric specific heat) of 'Gala' apple cultivar during the growing season in Pennsylvania using the (DNHP) method. Subsequently, the measured thermal properties during the growing season were used to evaluate and predict the harvest time and quality changes. Three thermal properties, i.e., thermal conductivity, thermal diffusivity, and specific heat were compared to each other to determine which one was, or ones were, the best predictor of the harvest time and quality changes.

CHAPTER 3

GOAL, OBJECTIVES, AND HYPOTHESES

Apple, cultivated worldwide, is one of the most economically valuable fruit in the USA, which is the second major apple-producing country. Apples are rich in nutrition including carbohydrate, fiber, organic acids, phenolic compounds, and variety of minerals and vitamins. They are processed into several products such as juice, sauce, vinegar, wine, candy jam, and canned, dried, and frozen products as well as being consumed fresh. Fresh apple and its products quality mostly depend on ripeness or maturity stage of the fruit. Many characteristics of apple have been used to estimate the harvest time, which are generally visual and physical properties (such as skin color, size, shape, firmness, tenderness, structure, and density), biochemical compositional factors (starch, sugar, acid content, ethylene concentration, and aroma compounds), and computation of time between flowering and fruit being ready for harvesting. Therefore, several destructive and non-destructive methods for the harvest time of apples have been reported.

Thermal properties are required for the design and the process during the manufacturing operation, and for food preservation, processing, storage, marketing, and consumption. Thermal properties; thermal conductivity, specific heat, and thermal diffusivity are associated with heat transfer and depend on composition, porosity (void fraction), moisture content, shape, size, density, homogeneity, fiber and their orientation. Thus, thermal properties of fruit might serve as an alternative physical properties and method in predicting the harvest time. The goal of this research is to investigate the possibility of thermal properties of 'Gala' apple cultivar as a means of determining the harvest time and its quality changes during the growing season.

Accordingly, the objectives of this research were to:

- measure 'Gala' apple thermal properties, i.e., thermal conductivity, thermal diffusivity, and specific heat during the growing season in Pennsylvania by using the dual needle heated probe (DNHP) method and examine the thermal property changes,

- determine the thermal properties at four different locations (sides) for each apple and to test whether the location has a significant effect on thermal properties measurement,
- measure the physical properties, i.e., size, density, and moisture content, that are considered to be related to thermal properties and examine the physical property change during the growing season,
- measure the conventional harvest and maturity indices including firmness, soluble solid content, and starch level during the growing season and examine the corresponding changes,
- examine the correlations among the measured thermal properties and the physical properties and the harvest fruit quality and maturity indices to explore the potential usage of thermal properties in predicting the harvest time.
- investigate which thermal property is, or properties are, the best predictor of the harvest time based on the changes in three thermal properties and their correlations with the harvest fruit quality and maturity indices during the growing season

The general hypotheses of this research were:

H_o: Thermal conductivity, thermal diffusivity, and specific heat values do not change significantly as the apple ripens ($p > 0.05$) and the changes are not moderately or strongly correlated to the harvest fruit quality and maturity indices ($|r| \leq 0.35$).

H_{A1}: Thermal conductivity, thermal diffusivity, and specific heat values change significantly as the apple ripens ($p > 0.05$) and the changes are moderately or strongly correlated to the harvest fruit quality and maturity indices ($|r| > 0.35$).

H_{A2}: Thermal conductivity, thermal diffusivity, and specific heat values change significantly as the apple ripens ($p > 0.05$) and the changes are not moderately or strongly correlated to the harvest fruit quality and maturity indices ($|r| \leq 0.35$).

CHAPTER 4

METHODOLOGY

4.1 General Overview and Flowchart of Methodology

The methodology of this research project consisted of four steps as depicted in Figure 9. In Phase I, the apple fruit samples were picked from the Penn State Fruit Research and Extension Center (FREC), Biglerville, PA during the 2017 growing season. Harvested apple samples were sent to Biological and Food Material (BFM) Properties Laboratory for the measurements. In Phase II, the physical properties, i.e., size, density, thermal properties, and moisture content, of apple samples were measured. Firstly, size and density of all apple samples were measured, then the DNHP apparatus was used for the measurement of thermal properties of apple samples. Subsequently, the moisture content of apple samples was measured. In Phase III, the select reference analysis of harvest fruit quality and maturity indices, i.e., soluble solid content, firmness, starch level, and Streif Index were determined to observe the efficacy of thermal property values for predicting the fruit quality and maturity. Finally, in Phase IV, all the data and results were interpreted by statistical analysis and the three hypotheses were tested. As the major outcome, a recommendation was made for the use of thermal properties to determine the apple harvest time using the quality and maturity indices relationships.

4.2 Facilities

This proposed research was performed in the BFM Properties Laboratory, Pennsylvania State University, University Park, PA. The DNHP, ThermoLink Meter, Instron, oven, and desiccator in this study were available in the BFM Properties Laboratory. The other needed items, plunger, and a refractometer were loaned from the FREC. A light box for taking images of apple for the starch level test was purchased.

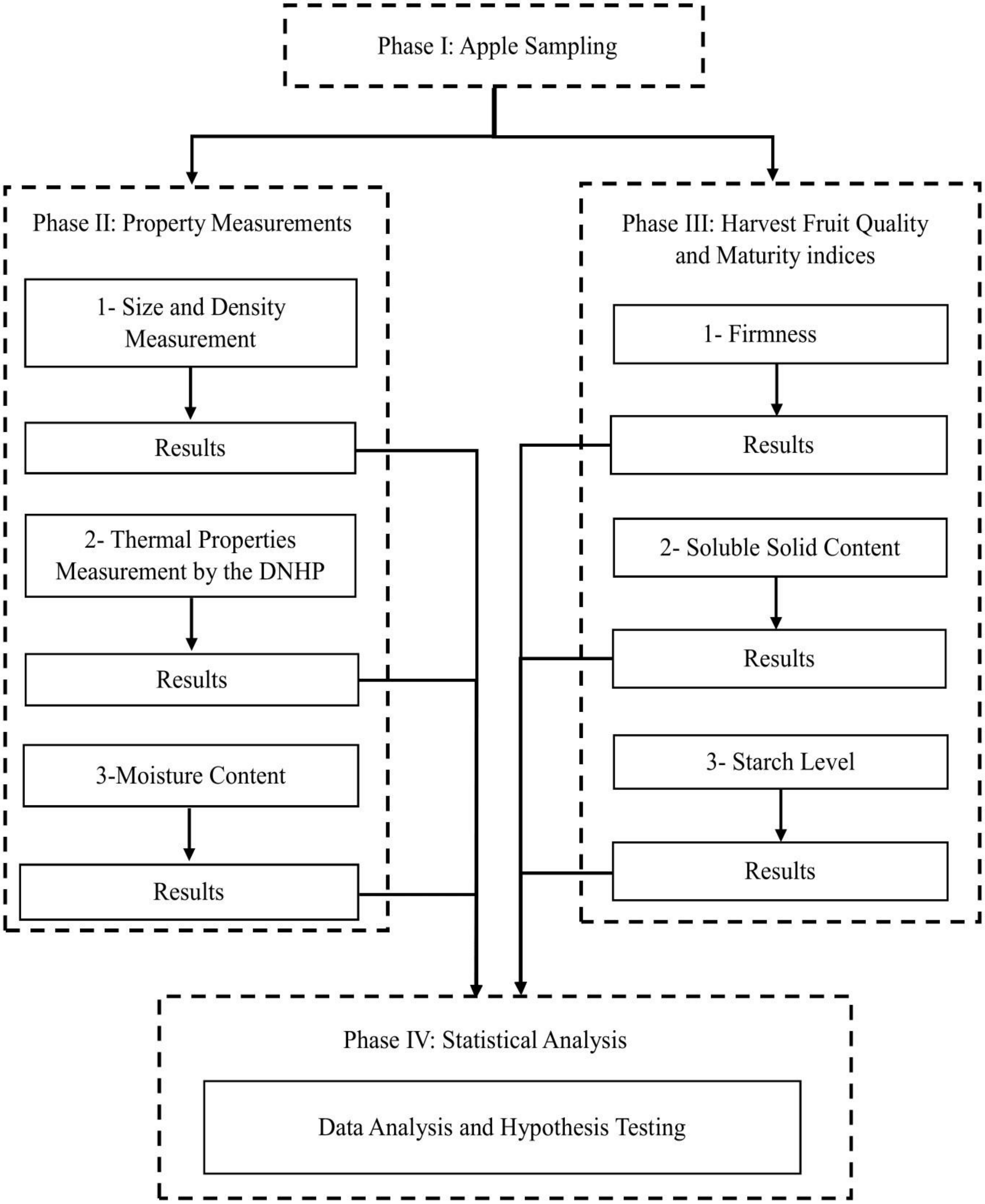


Figure 9 Flowchart of methodology

4.3 Detailed Methodology, Experimental Design, and Analysis

4.3.1 Apple Sampling

‘Gala’ apple samples were obtained each week from FREC, Biglerville, PA. Picking of apples for testing began on July 20 and concluded on September 8, 2017, which spanned the range from immature green to mature, to ripe apples. In total, eight sampling dates were defined based on fruit maturity: week 1-4 corresponding to immature cell enlargement of maturation stage, week 5-6 corresponding to the onset of physiological maturation, week 6-7 corresponding to ‘mature’ apples, and week 8 corresponding to ‘ripe’ apples as listed in Table 5. In this research, a total of 24 apple samples were non-selectively picked from the west side of four mature ‘Buckeye Gala’/M.9 trees in a tall spindle block with north-south rows. The picked apples were examined to ensure that they were free of any visible insect injury, disease or abiotic physical damage. Apple samples were transferred to the test laboratory on the main University Park campus within one day from the picking the date (Table 5). The measurements were started as soon as apple samples arrived in the lab (18-23°C) and were completed within a 24-hour period (Table 5).

Table 5 The development stage, sampling and measurement dates of ‘Gala’ apple cultivar during July 20-September 8, 2017 growing season

Week No	Development Stage	Sampling Date	Measurement Date
1	Cell Enlargement	07. 19. 2017	07.20.2017
2	Cell Enlargement	07. 25. 2017	07.26.2017
3	Cell Enlargement	08.02.2017	08.03.2017
4	Cell Enlargement	08.10. 2017	08.11.2017
5	Onset of Physiological Maturation	08.17.2017	08.18.2017
6	Physiological Maturation	08.24.2017	08.25.2017
7	Mature	08.31.2017	09.01.2017
8	Ripe	09.07.2017	09.08.2017

Sixteen of the 24 apple samples were used for measurement while remaining eight apple samples were for backup. The experimental design was as listed in Table 6. Firstly, size and density measurements were conducted, then, thermal properties of whole apple samples were measured at four locations that were 90° apart in the pole-to-pole (stem-calyx axis) direction. After the measurement of thermal properties of 16 apple samples, their firmness were measured at two opposite locations along the equator of apple samples; one each on the darkest and the lightest side. With these measurements completed, 12 out of 16 apple samples were randomly selected for soluble solid content (SSC), moisture content (MC), and starch level tests. Twelve apple samples were cut in half along the equator; the 12 halves of apple samples were used for SSC and MC measurements, and the remaining 12 halves of apple samples were used for the starch level test.

Table 6 Experimental design for weekly measurements during July 20-September 8, 2017 growing season.

Measurements		Number of Measurements per Apple	Number of Apples	Total Measurements
Properties	Size	1	3[a]	3
	Density	1	16[b]	16
	Thermal Properties	4	16[b]	64
	MC	1	12[c]	12
Harvest Fruit Quality and Maturity Indices	Firmness	2	16[b]	32
	SSC	2	12[c]	24
	Starch Level	1	12[c*]	12

[a]One each of large, medium, and small size of apples were used for size. [b]Density, thermal properties, and firmness of all 16 apples were measured, respectively. [c]12 halves of 16 apples were used for soluble solid content (SSC) and moisture content (MC) tests. [c*]The remaining 12 halves of apples were used for starch level test.

4.3.2 Property Measurements

4.3.2.1 Thermal Properties Measurement

4.3.2.1.1 Performance test of the DNHP and ThermoLink Meter

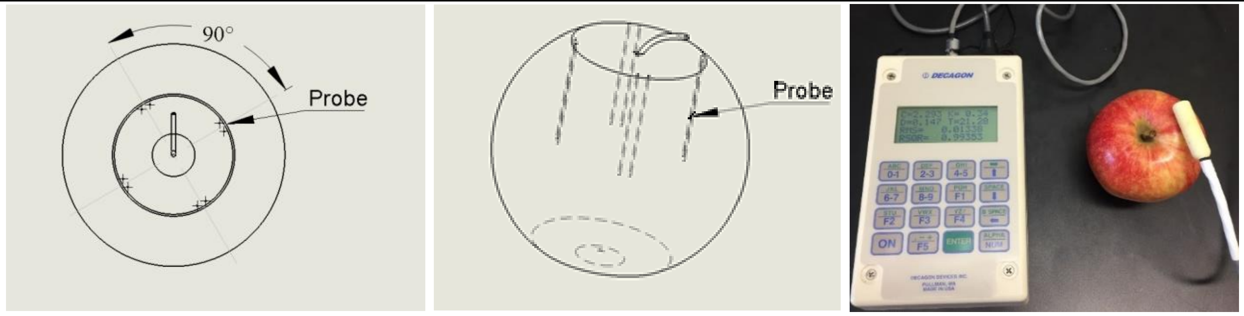
The performance verification and accuracy of the DNHP were tested using standard reference material (glycerol) based on a protocol conducted by Fontana et al., (1999). Glycerol (BDH1172) at room temperature (18-23°C) was poured into 10 different 150 mL beakers. The DNHP housing was held using a clamp and a metal stand to avoid any movement that would disturb heat propagation. The heating and temperature sensing needles were placed at the center of the beaker to avoid boundary effects of the beaker. All measurements were taken inside a Styrofoam box to maintain a temperature-stable environment. The RMSE (root-mean-square error) and percent difference between measured and reported glycerol value were then calculated. Further, to test the accuracy of ThermoLink Meter, ΔT (=Temperature at any time – Initial Temperature, degree C) vs. time (s) data obtained by ThermoLink Meter were used to calculate the best values of Q/L (J/m) by using the MATLAB program. The RMSE, percent difference between known and calculated Q/L values, and R^2 values were determined as well.

4.3.2.1.2 Thermal Properties Measurement of 'Gala' Apple

The DNHP used in this study for measuring thermal properties of 'Gala' apple samples consisted of two 30 mm long stainless steel 304 parallel needles spaced 6 mm apart. One needle contained a line heat source and another had a thermocouple. The DNHP was connected to a ThermoLink Meter (Decagon Devices, Inc., Pullman, WA), which is a microprocessor-controlled nanovoltmeter. The ThermoLink uses a heater and a thermocouple to find the thermal properties of a specimen in which the probe is inserted. The probe first equilibrated to within 0.0030°C of the initial temperature of the specimen, then measurements began. After equilibration, the heater needle emitted a heat pulse for eight seconds. At this point, the thermocouple needle began recording the temperature in the specimen for 60 seconds. During the recording, the microprocessor calculated the amount of power supplied to the heater and the probe's thermistor, measuring the changing temperature in the specimen (Fontana et al., 1999 & Operator's Manual; Decagon Devices, Inc., 1997). At the end of the recording, the ThermoLink Meter computed the thermal conductivity, thermal diffusivity, and volumetric specific heat of the specimen using the temperature difference (ΔT = Temperature at any time – Initial Temperature) vs. time data during measurement. However, the volumetric specific heat of samples were not used, the mass-based specific heat (C_p, kJ/kg-K) of apple samples were calculated on using equation (14). where k and D are obtained thermal conductivity and thermal diffusivity of samples from ThermoLink meter, respectively, and ρ is measured density of samples (Mohsenin, 1980).

$$C_p = \frac{k}{D\rho} * 1000 \tag{14}$$

Thermal properties of whole apple samples were measured at four different locations (sides) that were 90° apart as depicted with top view and 3D view in Figures 10a and 10b. The reason for measuring at these locations was that some portions of fruit on the tree received sunlight directly while other parts could be shaded, potentially resulting in spatially variable thermal conductivity. Also, due to the apple's biological nature, the flesh is typically not homogeneous and isotropic. Therefore, the darkest part, the lightest part (opposite of the darkest part), and the two locations in between the darkest and the lightest part of a whole apple samples were measured. The thermal property values of each apple were determined as the average of the four side values. For measurement, the DNHP was vertically inserted into the apple sample as seen in Figure 10c.



a) b) c)

Figure 10 DNHP four measurements locations 90° apart in apple samples, **a)** top view, **b)** 3D view, and **c)** DNHP measurement on apple samples.

The probes were cleaned before being used and after each measurement to remove residue left from previous samples that could affect the accuracy of next measurement. The cleaning procedure consisted of the following steps: water with soft and odorless detergent at 55°C, water,

water, distilled white vinegar, and water. The soft detergent was put into a 250 ml beaker filled with water, which was heated at a constant 55°C using Ultrasonic Cleaner (Bransonic®, Danbury, CT). The DNHP needles were held in this beaker filled with the detergent and water mix for approximately 15-20 seconds and rinsed with water in another beaker at room temperature. After rinsing twice, the DNHP needles were immersed in vinegar in a beaker for 10 seconds to remove any remaining residues and then rinsed for the last time before using.

4.3.2.2 Size

Three of the 16 apples (small, medium and large size of apples) were chosen and their outer dimensions (height (pole to pole) and diameter) were measured using a digital caliper (General® and Ultratech®, China) with 0-200 mm size range and resolution of ±0.01 mm. Three measurements were used for mean specimen dimension, including maximum (major principal, a), intermediate (intermediate principal, b), and minimum (minor principal, c). Two diameters (a, b) and one height (c) measurements were taken. The geometric mean diameter (GMD) of each apple sample was calculated based on a, b, and c using equation (15) (Mohsenin 1986).

$$GMD = (abc)^{1/3} \tag{15}$$

4.3.2.3 Density

Individual fruit was weighed in air and water using Instron (5000 N capacity, 2519-107 Model, Instron ®, Norwood, MA) with 0.0025 N resolution. The weight of apple samples was measured by tying the stem with a string to a flat plate with holes mounted on the Instron (Model 4344). Then, the secured sample was wholly immersed in distilled water using the Instron, since apples are less dense than water. The fruit densities (kg/m^3) were calculated using equation (16) where ρ_f is the fruit density, ρ_w is the water density, M_a is the weight of the fruit in the air, and M_w is the weight of the fruit in the water (Mohsenin, 1986). M_a and M_w were measured by the reading of load cell (5000 N with 0.0025 N resolution, Instron®, Norwood, MA) mounted on the Instron.

$$\rho_f = \frac{M_a}{M_a - M_w} \times \rho_w \tag{16}$$

4.3.2.4 Moisture Content (MC)

Apple samples were cut in half along the equator and the fruit core of the sample was removed. Fleshy parts of half of the apple sample were finely divided and approximately 20 g of the homogenized sample (M_S: mass of sample before drying) were placed into a flat-bottom metallic dish of known weight. The weighted apple samples were dried inside an oven at 70°C for 16-18 hours. After drying, the plates were placed into a desiccator (Dry-Keeper, Sanpla, Inc., Japan) to be cooled for approximately 24 hours and re-weighed. Weight was recorded as M_d (mass of sample after drying). The percentage moisture content was determined as shown in equation (17) (Ranganna, 1986; Ekpunobi et al., 2014).

$$\text{Moisture Content (MC)\%} = \frac{M_S - M_d}{M_d} \times 100\ (wet\ basis) \tag{17}$$

4.3.3 Harvest Fruit Quality and Maturity Indices

4.3.3.1 Firmness (F)

Fruit firmness can be measured with the Magness-Taylor pressure tester. The protocol was adapted based on the Penn State Extension, 2017 bulletin. The most critical factor in the firmness test is the plunger diameter with spherical head and plunger speed during force application. After removing a part of the peel at two points diametrically opposite at the equator location of each apple sample (the darkest side and the lightest side), the apple sample was placed in a holder to secure and minimize movement. The cylindrical plunger (11 mm diameter) was pushed into the fruit to a depth of 7.9 mm as marked on the plunger. The 11 mm diameter plunger, which is identical to a Magness-Taylor device was mounted on an Instron (Model 4344) with a 5000 N load cell with 0.0025 N resolution (Instron®, Norwood, MA). Instron speed was set to the requisite 3.95 mm/s. The force (N) applied for penetrating the apple through the depth of 7.9 mm were recorded using Bluehill 3 software (Version No: 3.24.1496, Instron ®, 2010). The average of peak force and force at 7.9 mm penetration from two locations for each apple were used as peak firmness and firmness at 7.9 mm penetration.

4.3.3.2 Soluble Solid Content (SSC)

Apple samples were cut in half along the equator, and the fruit core or pit of the samples was removed. A flesh part of one half of the apple samples was finely divided and homogenized. To determine total soluble solid content (SSC) of the apple samples, a digital refractometer (Atago, Inc., Japan) was used. The instrument was calibrated by zeroing with distilled water before using. Then, measurements were made by squeezing a small amount of juice from homogenized apple samples onto the prism of the refractometer. The instrument read the percentage of soluble solids using the Brix scale. After each measurement, the prism was rinsed and wiped with a soft tissue to prevent contamination among the sample readings (Skic et al., 2016; Penn State Extension, 2017). Two measurements were conducted for each half apple, and an average of two values for each apple was used.

4.3.3.3 Starch Index (SI)

All apple samples were cut in half along the equator and iodine solution which consists of 2.2 g of iodine crystals (Alfa Aesar, Word Hill, MA) and 8.8 g of KI (potassium iodide) (BDH0264) in 1 liter of water was applied (Blanpied & Silsby. 1992) to each one half of 12 apples at room temperature. After two minutes, dark blue color and yellowish color on each apple were observed and their pictures were taken in a light box (Favoitec ™, Studio PRO, China) with 50 W of LED and a camera with 16.2 megapixel resolution (D5100, Nikon Inc.) under the uniform indirect light condition with a background color (blue in this study) not found in the apple.

Starch index (SI) was visually determined based on the commonly used rating system with a scale of 1 to 8. **(1);** full core and flesh stain (all blue black - 100%), **(2);** half core stain (50%) and full flesh stain (100%), (**3**); clear core stain (0%) and full flesh stain (100%) **(4)**; clear stain in seed cavity and halfway to vascular area in flesh part (80%), **(5)**; clear through the area including vascular bundles in flesh part (60%), **(6)**; half of the flesh clear (40%), **(7)**; starch just under skin (20%), and **(8)**; free of starch (no stain - (0%) as seen in the Figure 11 (Blanpied & Silsby, 1992).

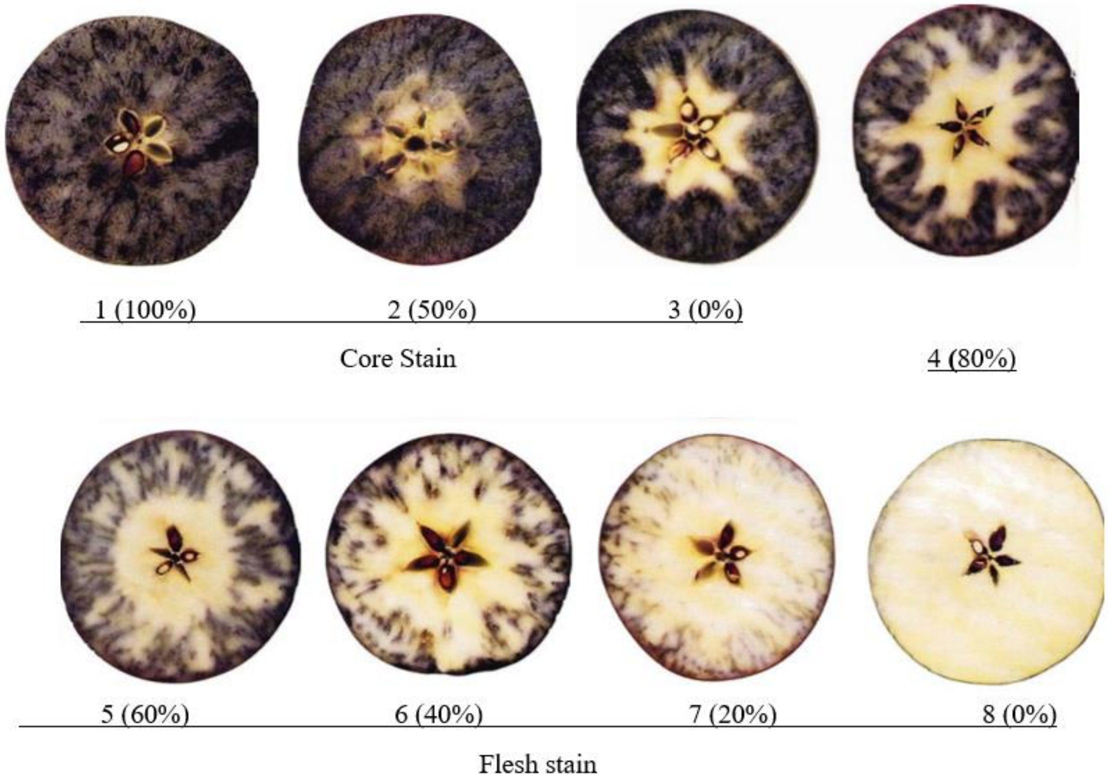


Figure 11 The rating system of starch level; the first row is the 1 to 8 rating system (Blanpied & Silsby, 1992).

Additionally, to quantify the core and flesh stain percentage of the samples, an image processing algorithm was developed using the MATLAB (R2017b, The MathWorks, Inc., Natick, MA) to eliminate the human subjectivity in the starch rating system (Figure 11). In the algorithm, image brightness was corrected to increase the contrast between the parts with and without iodine. The Circular Hough transform (CHT, Atherton and Kerbyson, 1999) was applied to find a circular object (apple) in the images. For an accurate measurement of core and flesh stain percentage, the core of the apple needs to be identified from the flesh (Figure 12a). Diameters of apple core and whole samples were measured and the average ratio of the core diameter were calculated as 45%, 44%, 42% and 39% of whole apple diameter for the week 1, 2, and 3, and the last five weeks, respectively. Then, the percentages of the iodine stain in the core and the flesh were calculated separately (Figure 12b). To identify the stain percentage in the apple, a threshold using a red component of the RGB (Red, Green, and Blue) format was set at 80-130 with 5 increments based on the image data set and applied. After the image processing with different thresholds, 125 was chosen as the best threshold for quantifying the percentages.

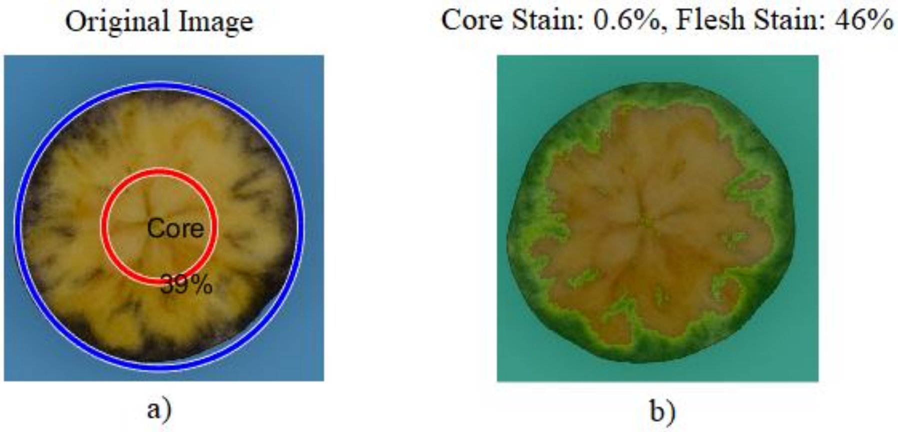


Figure 12 Starch test images of the week 7 obtained from the MATLAB, **a)** original image and **b)** percentage of core and flesh stain.

4.3.3.4 Streif Index (Maturity Index)

The Streif index comprised of three maturity measurements: soluble solid content, firmness, and starch index has been used to estimate the harvest time, which is specific for each cultivar (Streif, 1996; DeLong, et al., 1999; Peirs et al., 2005; Lotze & Bergh, 2012; Skic et al., 2016). It was calculated using an equation (18) with the Firmness (F) at 7.9 mm depth (in kg) of 12 apples out of 16 to match 12 measurements of SSC and SI for each week.

$$\text{Streif Index} = \frac{\mathrm{F}}{SSC * SI} \tag{18}$$

4.3.4 Statistical Analysis

Data analyses were carried out using a statistical analysis program, R (A language and Environment for Statistical Computing, R Core Team, Vienna, Austria, 2016). The analysis included calculations of mean values and standard deviations for all measured parameters, as well as the significance of value changes during the growing season with ANOVA ($p < 0.05$). Then, the significance in the property changes during the growing season was statistically tested with Tukey's Honestly Significant Difference, (HSD) with two different significance levels ($p < 0.05$ and 0.01) to highlight different significance levels of all 28 paired weeks during the growing season. Further, the strength of relationships among thermal properties of apple samples, the physical properties, and the harvest fruit quality and maturity indices were examined with Pearson correlation coefficients.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 The Measured ‘Gala’ Apple Properties

The physical properties, i.e., thermal properties, size, density, and moisture content of ‘Gala’ apple samples during the growing season were determined. In addition, changes in thermal properties, size, density, and moisture content of ‘Gala’ apple during the growing season were examined.

5.1.1 Thermal Properties

5.1.1.1 Accuracy of the DNHP and ThermoLink Meter

The thermal properties of apple samples were measured after performance test of the DNHP using glycerol at room temperature. The ThermoLink Meter computed the thermal properties of glycerol using the change in temperature (ΔT) over a specific period. The measured thermal conductivity and thermal diffusivity of glycerol in this study were 0.313 ± 0.014 W/m-K and 0.103 ± 0.003 mm^2/s at 21.44 ± 0.11°C. Thermal conductivity and thermal diffusivity of glycerin measured by the probe method were reported as 0.286 W/m-K and 0.096 mm^2/s at 27°C, respectively (Rahman, 2009) and 0.29 W/m-K and 0.105 mm^2/s at 23°C, respectively (Fontana et al., 1999). The mean RMSE and percent difference of thermal conductivity and thermal diffusivity values between measured and reference values were 0.028 and 0.005, and 7.8 ± 4.2% and 4.4 ± 2.4%, respectively. In the literature, the accuracy of DNHP of 3.1% and 10.3% for measurement of thermal conductivity and thermal diffusivity, respectively was reported by Fontana et al. (1999). When our data were compared with the reported data, the accuracy of thermal conductivity (7.8%) and thermal diffusivity (4.4%) were similar. Therefore, the DNHP method was determined acceptable.

Also, the best value of Q/L (J/m) to verify the accuracy of ThermoLink Meter was found to be 362.25 ± 0.06 J/m, which is nearly same as the known Q/L value (362.2 J/m) provided by the manufacturer of ThermoLink Meter. In addition, RMSE, the percent difference between known and calculated Q/L values, and R^2 values were found to be 0.0027 ± 0.0017, 1.244 ± 0.0743%, and 0.9994 ± 0.0007, respectively.

5.1.1.2 Thermal Properties of 'Gala' Apple

The average of thermal conductivity (k), thermal diffusivity (D), and specific heat (C_p) values of four sides of apple samples during growing season decreased from 0.445 to 411 W/m-K, 0.152 to 137 mm^2/s, and 4.23 to 3.93 kJ/kg-K with mean temperature of apple from 19.1 to 22.6°C, respectively, (Table 7). The measured thermal property values during the last two to three weeks fell within the reported range of thermal conductivity, thermal diffusivity, and specific heat for different cultivars of mature apples (0.370 - 0.513 W/m-K, 1.33 - 1.46 mm^2/s, and 3.493 - 4.038 kJ/kg-K, respectively) (Sweat, 1974; Donsi et al., 1996; Fontana, et al., 1999; Liang et al., 1999; Mykhailyk & Lebovka, 2013).

Average thermal conductivity remained stable during the first six weeks ranging between 0.437 and 0.454 W/m-K and then decreased to 0.429 and 0.411 W/m-K at the week 7 and the week 8, respectively. Similarly, average thermal diffusivity remained stable during the first six weeks, ranging between 0.146 and 0.152 mm^2/s and then decreased to 0.142 and 0.137 mm^2/s in the week 7 and the week 8, respectively. Average thermal conductivity and thermal diffusivity values decreased as the apples fully matured and ripened. However, the specific heat of apples had no consistent trend as the fruit ripened. The C_p values decreased until the week 5 then increased in the week 6 and 7, followed by a decrease in the week 8.

The statistical significance of changes in thermal conductivity, thermal diffusivity, and specific heat values of 'Gala' apple during the growing season were tested with ANOVA ($p < 0.05$). As listed in Table 8, weekly changes in thermal conductivity (with $F = 14.0 > F_{critical} = 2.1$ and $p < 0.0005$) and thermal diffusivity (with $F = 9.5 > F_{critical} = 2.1$ and $p < 0.0005$) changes were significant during the growing season. However, weekly specific heat (with $F = 1.7 < F_{critical} = 2.1$ and $p = 0.11 > 0.05$) did not change during the growing season.

Table 7 The average of the physical properties of ‘Gala’ apple during the growing season (July 20, 2017 - September 8, 2017).

Sampling date	k (W/m-K)	D (mm^2/s)	C_p (kJ/kg-K)	Temperature* (°C)	Size (mm)	ρ (kg/m^3)	MC (wb %)
Week 1 (July 20, 2017)	0.445 ± 0.014^{ab}	0.146 ± 0.005^{ab}	4.23 ± 0.25^{a}	21.9 ± 0.6	58.2 ± 3.2^{a}	724.1 ± 45.9^{a}	84.7 ± 0.6^{a}
Week 2 (July 26, 2017)	0.446 ± 0.021^{bc}	0.151 ± 0.007^{a}	4.08 ± 0.36^{a}	20.4 ± 0.2	60.8 ± 5.8^{a}	730.2 ± 35.6^{a}	84.5 ± 0.6^{ab}
Week 3 (Aug 3, 2017)	0.454 ± 0.015^{b}	0.152 ± 0.006^{a}	4.05 ± 0.26^{a}	21.5 ± 0.4	65.3 ± 4.0^{a}	742.9 ± 33.0^{a}	84.4 ± 1.1^{ab}
Week 4 (Aug 11, 2017)	0.442 ± 0.010^{abc}	0.151 ± 0.011^{a}	3.94 ± 0.42^{a}	20.9 ± 0.3	67.5 ± 7.5^{a}	752.5 ± 33.4^{a}	83.8 ± 0.4^{abc}
Week 5 (Aug 18, 2017)	0.437 ± 0.015^{ac}	0.148± 0.006^{ab}	3.93 ± 0.20^{a}	22.6 ± 0.5	70.0 ± 7.6^{a}	756.4 ± 22.4^{a}	83.9 ± 0.8^{abc}
Week 6 (Aug 25, 2017)	0.444 ± 0.010^{ab}	0.147 ± 0.005^{ab}	4.02 ± 0.19^{a}	21.0 ± 0.4	69.3 ± 5.7^{a}	756.8 ± 24.3^{a}	83.7 ± 0.8^{bc}
Week 7 (Sept 1, 2017)	0.429 ± 0.012^{a}	0.142 ± 0.007^{bc}	4.09 ± 0.37^{a}	20.1± 0.3	68.1 ± 9.6^{a}	748.0 ± 34.0^{a}	83.3 ± 0.6^{c}
Week 8 (Sept 8, 2017)	0.411 ± 0.015^{d}	0.137 ± 0.004^{c}	3.96 ± 0.20^{a}	19.1 ± 0.2	69.6 ± 9.0^{a}	762.8 ± 23.7^{b}	83.3 ± 0.7^{c}

k: thermal conductivity, D: thermal diffusivity, and C_p: specific heat, ρ: density, and MC: moisture content based on a wet basis (wb%). The superscript letters (a, b, c, d, e, f) denotes the column based significant differences (based on Tukey's HSD with $p < 0.05$). The same superscript letter denotes no significant differences.

Table 8 Summary of ANOVA table

Properties	Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	F	P value
k (W/m-K)	Factor	7	0.0202	0.0028	14.0	0.0000
	Error	120	0.0247	0.0002		
D (mm^2/s)	Factor	7	0.0031	0.0004	9.5	0.0000
	Error	120	0.0055	0.0001		
c_p (kJ/kg-K)	Factor	7	1.15	0.1643	1.7	0.11
	Error	120	11.43	0.0953		
Size (mm)	Factor	7	402.6	57.51	1.220	0.35
	Error	16	754.1	47.14		
ρ (kg/m^3)	Factor	7	20309	2901.2	2.775	0.01
	Error	120	125441	1045.3		
MC (wb%)	Factor	7	23.3	3.32	6.18	0.0000
	Error	87	46.7	0.54		

$F_{critical} = F_{(0.05,\ 7,\ 120)} = 2.09$, $F_{(0.05,\ 7,\ 87)} = 2.12$, and $F_{(0.05,\ 7,\ 16)} = 2.66$. k: thermal conductivity, D: thermal diffusivity, C_p: specific heat, ρ: density, and MC: moisture content based on wet basis (wb%).

To further investigate which week resulted in significant changes in thermal conductivity and thermal diffusivity, Tukey's HSD was performed with two different significance levels ($p < 0.05$ and $p < 0.01$) as denoted with superscript letters in Table 7. There were significant changes in thermal conductivity for both the week 7 and the week 8. In detail, the week 8 thermal conductivity values were significantly different from weeks 1 through 7 ($p < 0.01$), the week 7 thermal conductivity values were significantly different from the week 2 ($p < 0.05$) and the week 3 ($p < 0.01$), and the week 5 thermal conductivity values were significantly different from the week 3 ($p < 0.05$). The observed significant difference in the thermal conductivity of last two weeks, particularly the week 8, suggests that maturity of apple can be detected with changes in thermal conductivity.

Similarly, the week 8 thermal diffusivity was significantly different from weeks 1 through 7 ($p < 0.01$) and the week 7 thermal diffusivity was significantly different from weeks 2, 3, and 4 ($p < 0.01$) as denoted with superscripts in Table 7. Overall, thermal conductivity and diffusivity values changed as apple ripened, particularly in the week 7 and the week 8 that correspond to fully mature and ripe samples. Apples of these maturity stages are considered either optimum for consumption and/or short-term storage (Westwood, 1993) Thermal properties of foods are thought to be dependent on composition and factors affecting the heat flow paths through material such as porosity, moisture content, shape, size, homogeneity, and fiber and their orientation (Mohsenin, 1980; Rahman, 1991). Accordingly, the changes in thermal conductivity and thermal diffusivity apples during the maturation and ripening stage were expected, particularly after the week 6, when major physical, biochemical, and physiological changes that affect the fruit quality and maturity occur (Westwood, 1993).

Fruit maturity and ripening accompany physical and visual changes such as altered texture, decreases of firmness and skin chlorophyll, increases of carotenes, xanthophylls (green to yellow), and anthocyanins (red overcolor), and biochemical and physiological changes, i.e., a decrease of starch, acidity, air respiratory activity, and an increase of sugars, soluble solids, and soluble pectins. These changes are usually preceded by or accompany a surge of CO_2 evolution and ethylene production once ripening initiates for a climacteric fruit such as pple (Westwood, 1993, Salunke, 1995, Castro-Giraldez, et al., 2010). Hence, the changes in thermal properties during the growing season, especially the last week, might be related to ethylene production.

5.1.1.3 Thermal Properties of ‘Gala’ Apple at Different Locations

Location of measurement may affect the thermal property value because the dimension of DNHP is much smaller than an apple. To examine potential spatial differences of thermal properties, thermal conductivity (k), thermal diffusivity (D), and specific heat (C_p) of each apple were measured at four different locations reflecting four different sides. From ANOVA test, thermal conductivity was found to be significantly different depending on the sides of an apple ($p < 0.05$) during the growing season. However, thermal diffusivity and specific heat were not different depending on sides of an apple ($p > 0.05$) except the last week D ($p = 0.029 < 0.05$) and the first week C_p ($p = 0.41 < 0.05$).

Respective thermal conductivity at each location was compared by Tukey's HSD with $p < 0.05$. Thermal conductivity of the darkest part of apple was significantly different ($p < 0.05$) from the lightest part of apple during the growing season except for the week 5, which correspond to the onset of physiological maturation, and the week 7 when apples fully matured as denoted with superscripts in Table 9. Furthermore, thermal conductivity of the darkest part of apple was significantly different from the partly dark part of apple at weeks 1, 5, 6, and 8 ($p < 0.05$). However, significant differences were not observed between opposite sides of the partly dark side and the partly light side during the growing season ($p > 0.05$).

Table 9 Thermal conductivity (k) values (W/m-K) of apple samples based on the side values.

Sampling Date	Darkest side	Partly dark side	Lightest side	Partly light side
Week 1 (July 20, 2017)	0.466 ± 0.026^{a}	0.441 ± 0.019^{b}	0.437 ± 0.018^{b}	0.435 ± 0.023^{b}
Week 2 (July 26, 2017)	0.462 ± 0.030^{a}	0.443 ± 0.031^{ab}	0.438 ± 0.020^{b}	0.443 ± 0.020^{ab}
Week 3 (Aug 3, 2017)	0.470 ± 0.019^{a}	0.453 ± 0.024^{ab}	0.446 ± 0.014^{b}	0.449 ± 0.017^{b}
Week 4 (Aug 11, 2017)	0.453 ± 0.013^{a}	0.443 ± 0.011^{ab}	0.438 ± 0.014^{b}	0.436 ± 0.021^{b}
Week 5 (Aug 18, 2017)	0.450 ± 0.018^{a}	0.429 ± 0.013^{b}	0.433 ± 0.022^{ab}	0.436 ± 0.023^{ab}
Week 6 (Aug 25, 2017)	0.457 ± 0.012^{a}	0.438 ± 0.014^{b}	0.443 ± 0.014^{b}	0.438 ± 0.015^{b}
Week 7 (Sept 1, 2017)	0.439 ± 0.018^{a}	0.430 ± 0.025^{a}	0.423 ± 0.011^{a}	0.425 ± 0.021^{a}
Week 8 (Sept 8, 2017)	0.427 ± 0.024^{a}	0.405 ± 0.022^{b}	0.404 ± 0.012^{b}	0.407 ± 0.012^{b}

*a, b, the superscript letters denote the row based significant differences (according to Tukey's HSD with $p < 0.05$). The same superscript letter denotes no significant differences.

The observed significant differences between the thermal conductivity of the darkest and lightest sides can be explained by the observation that the sun-exposed side and shaded side of an apple have different quality and different postharvest characteristics even in the same tree. Similarly, many properties of apples including size, color, weight, soluble solid content, enzymatic and non-enzymatic antioxidants, firmness, and ethylene peak level are different depending on the degree of exposure to sunlight (Barritt et al., 1996; Ma & Cheng, 2004; Thompson, 2015). The observations in this work corroborate the findings of Sweat (1974) that the thermal conductivity can change within the same fruit. Accordingly, it is concluded that thermal conductivity measurement should be performed on at least two different locations, preferably the darkest and lightest sides for each sample, to ensure the measurement is an accurate representation of overall apple thermal properties.

5.1.2 Size of ‘Gala’ Apple

The average size values of ‘Gala’ apple samples were between 58.2 and 70.0 mm during the growing season (Table 7). Mature fruit sizes were reported in the range of 60 – 70 mm (Liang et al., 1999; Westwood, 1993). As expected, the average size of apple samples gradually increased from 58.2 to 70.0 mm during the first four weeks which corresponded cell enlargement stage. Then, the size of apples during the last three and four weeks corresponding the physiological maturation and ripening stage was between 68.1 to 70.0 mm. This fruit growth can be explained by increases in volume and weight, which are attributed predominantly to cell division during this early phase of fruit development. After cell division is completed, cell enlargement begins at a rapid rate as air space formations occur. The subsequent internal fruit growth occurs mainly due to cell expansion (Westwood, 1993; Salunke, 1995). The changes in fruit size as it grows are frequently used to determine the harvest time because the fruit size, shape, and weight at harvest affect the profitability during marketing (Thompson, 2015). However, these changes in the size of ‘Gala’ apple during the growing season, in this study, were not significant (ANOVA, $p > 0.05$) as shown in Table 8. This might be explained by the fact that the measurements started once apples were almost full size.

5.1.3 Density of ‘Gala’ Apple

The average density (ρ) of ‘Gala’ apple samples during the growing season were between 724.1 and 762.8 kg/m^3 (Table 7). There was no consistent change in density of apple during the growing season. The density of ‘Gala’ apple increased gradually during weeks 1 through 4 and the values remained almost same in both the week 5 and the week 6. Then, density values decreased in the week 7 but increased again in the week 8. This might be explained by the changes in density of apple samples during the maturation stage, which consists of cell division and cell enlargement accompanied by increases in intercellular and capillary air spaces (Thompson, 2015).

Although there was no consistent trend, the changes in apple density during the growing season were significantly different (ANOVA, $p < 0.05$) only between the week 1 and the week 8 as denoted with superscripts in Table 7. Thompson (2015) reported that fruit specific gravity increases as fruit matures. Mature apple density was reported in the range of 790 – 840 kg/m^3 (Sweat, 1974; Rahman, 2009), which are similar to the measured density in this study.

5.1.2.3 Moisture Content (MC) of 'Gala' Apple

The average of moisture content (wet basis) of 'Gala' apple were between 83.3 and 84.7% during the growing season, which is within the ranges of reported values (Table 7). The moisture content of 'Gala' apple during the growing season varies from 75 to 90% based on the cultivar, stage of development, maturity, and several climatic factors (Salunke, 1995). Mature apple moisture content was also reported in the range of 84 – 85% (Sweat, 1974; 1999; Westwood 1993, Rahman, 2009).

Overall, the moisture content of 'Gala' apple had a decreasing trend. The changes in moisture contents are found to be significantly influenced by the picking week (ANOVA, $p < 0.05$). Tukey's HSD ($p < 0.05$ and $p < 0.01$) tests were performed to identify week-pairs with the significant differences as denoted with superscripts in Table 7. Both the week 7 and the week 8 MC values were significantly different from the week 1 and the week 2 ($p < 0.01$) and the week 3 ($p < 0.05$), and the week 6 MC values were significantly different from the week 1 ($p < 0.05$). The reason for the significant changes might be explained with respiration rate, which increases with the initiation of the ripening stage. Thus, respiration rate could be the factor for decreasing water content in fruit (Westwood, M.N., 1993, Salunke, 1995, Castro-Giraldez, et al., 2010).

Further, thermal conductivities of food materials are known to increase with moisture content because dry porous solids are poor heat conductors since the pores in materials are associated with air instead of water (Mohsenin, 1980; Sahin & Gulum Sumnu, 2006). The water content of fruits and vegetables was reported to be a dominant factor in determining their thermal conductivities (Liang et al., 1999). In the literature, thermal conductivity of apple at various moisture contents was found to decrease with moisture content decrease (Lozano et al., 1979; Donsi et al., 1996; Zhang et al.,2011). Thus, the decrease in thermal conductivity might be related to a decrease of moisture content.

5.2 Harvest Fruit Quality and Maturity Indices

In practice, apple maturity is determined by the conventional harvest and maturity indices including firmness, soluble solid contents, starch level, and Streif Index. To examine the feasibility of using thermal properties of apple to determine apple maturing or ripening, these conventional apple maturity indices were determined along with the thermal properties.

5.2.1 Firmness (F) of 'Gala' Apple

The averages of the first peak value of firmness and firmness at a depth of 7.9 mm of 'Gala' apple are listed in Table 10. Both peak value of firmness and firmness at a depth of 7.9 mm during the growing season had similar decreasing trend from 88.4 to 57.5 N and 88.7 to 56.1 N, respectively. Also, when comparing both the peak value of firmness and the firmness at 7.9 mm penetration during the 2017 growing season, there was no significant difference ($p > 0.05$) although the 7.9 mm force is in the deeper layer of fruit tissue than the peak value (at penetration < 7.9 mm). This is because the first peak force, known as the bioyield point before sudden drop, indicates permanent cell deformation then the material's resistance to deformation usually loses its strength to applied force beyond this point (Mohsenin, 1986; Lu et al., 2005; Singh & Reddy, 2006).

The changes in both the peak value of firmness and the firmness at depth of 7.9 mm during the growing season were significant (ANOVA, $p < 0.05$). Tukey's HSD ($p < 0.05$ and $p < 0.01$) were performed to investigate further which week resulted in the significant changes as denoted with superscripts in Table 10. Specifically, the week 8 firmness values were different from weeks 1 through 4 ($p < 0.01$) and the week 5 ($p < 0.05$), both the week 6 and the week 7 firmness values were different from weeks 1, 2, and 3 ($p < 0.01$), the week 7 firmness values were also different from the week 4 ($p < 0.05$), both the week 4 and the week 5 firmness values were different from the week 1 and the week 2 ($p < 0.01$), and the week 3 firmness values were different from the week 2 ($p < 0.05$).

Apple firmness changes during the maturation particularly during the ripening stage in which they quickly become softer (Kader, 1999; Brummel, 2006; Thompson, 2015). The fruit firmness is a function of the cell wall and bonding between neighboring cells and contents of the cells. During the fruit ripening, cell-to-cell bonding weakens with hydrolysis of middle lamella pectin; thus, fruit tissues become soft (De Bellie et al., 2000). A study on ‘Gala’ apple was conducted during the growing season (July 31 – Sept 26, 2003) at the 10-day interval, the firmness of ‘Gala’ apple decreased from approximately 130 to 60 N (Lin & Walsh, 2008). Another study on the measurement of the firmness of ‘Gala’ apple at various dates (80 – 200 days after fool bloom, DAFB) during the growing season was conducted. The firmness of ‘Gala’ apple declined linearly from approximately 130 to 40 N (Volz et al., 2003). Also, the optimum requirement of the firmness of ‘Gala’ apples based on consumer expectations were reported as 58.6 N (Hoehn et al., 2003). The firmness values of ‘Gala’ apple during the growing season in this study were in the range of these reported data.

Additionally, the firmness of ‘Scarlet’ apples picked every fifth day during August-October period was measured. In this case, harvesting began three weeks before the presumed harvest date (8 harvests) and continued for two weeks later (2 harvests). The measured firmness values decreased from 73 to 65 N and 58 to 57 N, respectively (Bertone et al., 2011). The firmness of ‘Szampion’ and ‘Ligol’ apple cultivars during the growing season was reported between approximately 105 to 58 N and 115 to 62 N, respectively (Skic et al., 2016). In addition, the firmness values of ‘Rhode Island Greening’ apple during the growing season (Sept 10 and Oct 10) were reported between 110 and 90 N (Blanpied & Silsby, 1992). Also, they reported that seasonal climatic factors, as well as such orchard factors as nutrition and cropping level frequently influence the apple ripening indexes (Blanpied & Silsby, 1992). From these publications, the measured firmness value is dependent of on the apple variety, growing conditions, and harvesting time as well.

Table 10 The average of harvest and maturity indices of ‘Gala’ apple during the growing season (July 20 to Sept 8, 2017).

Sampling date	F (N) (Peak point)	F (N) (at 7.9 mm)	SSC (°Brix)	SI (1-8) (mode)*	Flesh Stain %	Streif Index
Week 1 (July 20, 2017)	88.4 ± 13.3^{ab}	88.7 ± 11.0^{ab}	9.3 ± 0.3^{a}	1.7 ± 0.5^{a} (2)	97.1 ± 3.4^{a}	0.64 ± 0.28^{a}
Week 2 (July 26, 2017)	90.2 ± 12.6^{a}	87.2 ± 10.2^{a}	9.7 ± 0.3^{ab}	2.1 ± 0.3^{ab} (2)	91.85 ± 4.1^{a}	0.45 ± 0.07^{bc}
Week 3 (Aug 3, 2017)	77.2 ± 12.4^{bc}	78.4 ± 8.3^{bc}	9.8 ± 0.5^{ab}	2.0 ± 0.4^{ab} (2)	94.1 ± 5.5^{a}	0.42 ± 0.15^{bcd}
Week 4 (Aug 11, 2017)	72.7 ± 9.6^{cd}	72.6 ± 8.0^{cd}	10.3 ± 0.3^{bc}	2.2 ± 0.4^{ab} (2)	90.0 ± 7.6^{a}	0.34 ± 0.07^{cde}
Week 5 (Aug 18, 2017)	69.0 ± 5.8^{cde}	68.3 ± 6.8^{cde}	10.9 ± 0.8^{cd}	2.5 ± 0.5^{ab} (2)	95.6 ± 2.3^{a}	0.27 ± 0.07^{de}
Week 6 (Aug 25, 2017)	65.0 ± 6.3^{def}	66.2 ± 6.4^{def}	11.5 ± 0.5^{d}	3.4 ± 0.9^{c} (4)	92.7 ± 5.8^{a}	0.19 ± 0.06^{ef}
Week 7 (Sept 1, 2017)	60.4 ± 9.2^{ef}	62.5 ± 10.0^{ef}	12.5 ± 0.6^{e}	4.8 ± 0.9^{d} (4)	75.4 ± 16.2^{b}	0.11 ± 0.03^{f}
Week 8 (Sept 8, 2017)	57.5 ± 6.5^{f}	56.1 ± 6.3^{f}	13.0 ± 0.5^{e}	5.2 ± 0.9^{d} (5)	68.7 ± 16.9^{b}	0.09 ± 0.03^{f}

F: firmness, SSC: soluble solid content, and SI: starch index. *The mode values of starch index were given in parentheses. The superscript letters (a, b, c, d, e, f) denote the column based significant differences (based on Tukey's HSD with $p < 0.05$). The same superscript letter denotes no significant differences.

5.2.2 Soluble Solid Content (SSC) of ‘Gala’ Apple

The average of the total soluble solid content of ‘Gala’ apple regarding the harvest date increased from 9.3 to 13.0°Brix as illustrated in Table 10. The SSC values remained stable during the first three weeks ranging between 9.3 and 9.8, then it increased to 10.3, 10.9, 11.5, 12.5, and 13.0 in weeks 4, 5, 6, 7, and 8, respectively. The changes in SSC values during the growing season were significant (ANOVA, $p < 0.05$). Tukey’s HSD ($p < 0.05$ and $p < 0.01$) were performed to investigate further which week resulted in the significant changes as denoted with superscripts in Table 10. The SSC values of ‘Gala’ apple for both the week 8 and the week 7 were significantly different from weeks 1 through 6 ($p < 0.01$). In addition, the week 6 SSC values were significantly different from weeks 1 through 4 ($p < 0.01$), the week 5 SSC values were significantly different from weeks 1, 2, and 3 ($p < 0.01$), and the week 4 SSC values were significantly different from the week 1 ($p < 0.01$).

Carbohydrates of climacteric fruit are accumulated in the form of starch in early stage, and they are hydrolyzed into sugars (monosaccharides, mainly glucose and fructose) as the fruit ripens. Sugar content is the major component of soluble solids and prone to increase as apples ripen. Similar to our study, a study on ‘Gala’ apple was conducted during the growing season (July 31 – Sept 26, 2003) at 10-day intervals and total soluble solid content of ‘Gala’ apple increased from approximately 11 to 16% (Lin & Walsh, 2008). In another study on ‘Gala’ apples, the SSC values at three different maturity groups (immature (Aug 12), mature (Aug 22), and overripe (Sept 2) in 2002) were 14.7, 14.9, and 14.3, respectively (Pathang, et al., 2006). The optimum requirement of SSC of ‘Gala’ apple based on consumer expectations was reported as 12.3°Brix (Hoehn et al., 2003). The SSC values for ‘Gala’ apple in this study were similar and in the range of the reported data.

Further, the SSC value of different varieties of apple fruit was compared with our results. For example, a study conducted on Scarlet apples during August-October period, total SSC during first eight and last two harvests increased from 10.1 to 12.2°Brix and decreased to 13.0 to 12.7°Brix, respectively (Bertone, et al., 2011). Total SSC of ‘Szampion’ and ‘Ligol’ apple cultivar during the growing season (July 3 – October 4) was reported to be between 9.30 and 14.66°Brix and 8.34 and 13.18°Brix, respectively (Skic, et al., 2016). In addition, the SSC values of ‘Rhode

Island Greening' apple during the growing season (Sept 10 - Oct 10) were reported between approximately 9.8 and 12.2°Brix (Blanpied & Silsby, 1992). As reported, these data and maturity time change based on apple variety since every variety has different chemical content. For example, the SSC of 'Golden Delicious' (in August), 'Fuji' (in September), 'Orin' (in October), and 'Granny Smith' (in October) at maturity time were reported as 13.40, 13.84, 13.81, and 12.03°Brix, respectively (Wu et al., 2006). Overall, the SSC values of apple fruits were between 9-14°Brix and varies based on apple variety and growing conditions.

5.2.3 Starch Index (SI) of 'Gala' Apple

Starch index increases as the flesh stain decreases. The rated starch index based on the study (Blanpied & Silsby, 1992) increased from 1.7 to 5.2 with most frequent SI values for each week as seen in Table 10. The SI of 'Gala' apple remained stable between 1.7 and 2.5, but it increased to 3.4, 4.8, and 5.2 in weeks 6, 7, and 8, respectively. The changes in percentage values of flesh stain and starch index during the growing season were significant (ANOVA, $p < 0.05$). Tukey's HSD ($p < 0.05$ and $p < 0.01$) tests were performed to investigate which week resulted in the significant changes as denoted with superscripts in Table 10. Both the week 7 and the week 8 SI values were significantly different from weeks 1 through 6 ($p < 0.01$), the week 6 SI values were significantly different from weeks 1 through 4 ($p < 0.01$) and the week 5 ($p < 0.05$), and the week 5 SI values were significantly different from the week 1 ($p < 0.05$). The observed significant difference in the starch index of last two and/or three weeks can be pointed as a sign of the maturity of apple.

The result of flesh stain percentage during the growing season obtained from the MATLAB decreased from 97.1 to 68.7% (Table 10). The percentage of flesh stain values remained stable during the first six weeks from 97.1% to 90.0, then it decreased to 75.4% and 68.7% in the week 6 and the week 7, respectively. The changes in the flesh stain percentages during the growing season were significant (ANOVA, $p < 0.05$). Tukey's HSD ($p < 0.05$ and $p < 0.01$) were performed to further investigate which week resulted in the significant changes as denoted with superscripts in Table 10. Both the week 7 and the week 8 flesh stain percentages were significantly different from weeks 1 through 6 ($p < 0.01$).

A study on ‘Gala’ apple was conducted during the growing season (July 31 -Sept 26, 2003) with harvesting at a 10-day interval. The starch index values of ‘Gala’ apple increased from 1 to 7 (Lin & Walsh, 2008). In another study, starch index (1-9) of ‘Gala’ apples at three different maturity groups (immature (Aug 12), mature (Aug 22), and over-ripe (Sept 2) in 2002) were 2.4, 5, and 7.1, respectively (Pathang, et al., 2006). In the study conducted on ‘Scarlet’ apples during August-October period, the SI of ‘Scarlet’ apples during the first eight and last two harvests increased from 1.8 to 7.5 and 8.4 to 9.5, respectively (Bertone et al., 2011). The reported starch content of ‘Szampion’ and ‘Ligol’ apple cultivar during the growing season (July 3 – October 4) was initially stable during the first five sampling dates and significantly diminished during the last three sampling dates. The decrease of starch content was a result of starch granule hydrolysis into simpler carbohydrates during the apple maturation. When the SI of ‘Szampion’ and ‘Ligol’ apples is between five to seven and six and eight, they should be harvested at the 6th and 7th sampling dates, respectively (Skic, et a.l, 2016). Further, the SI values of ‘Rhode Island Greening’ apple during the growing season (Sept 10 - Oct 10) were reported between approximately 2 and 5 (Blanpied & Silsby, 1992). When compared, the reported starch index values of apple during the growing season were similar to those in this study. Albeit small, the differences can be attributed to the fruit variety, growing conditions, different harvesting time for measurements, and different starch rating level

5.2.4 Streif Index (Maturity Index) of ‘Gala’ Apple

The average of Streif Index regarding picking date decreased from 0.64 to 0.09 as listed in Table 10. The Streif Index values were between 0.64 and 0.34 during the first four weeks corresponding to immature cell enlargement, then it decreased to 0.27 for apples at the onset of physiological maturation (the week 5), to 0.190 and 0.11 for mature apples (weeks 6 and 7), and to 0.09 for ripe apples (the week 8), respectively. The decline in Streif Index values during the growing season is a consequence of the maturing fruit’s decreasing firmness and the increasing SSC and SI. For optimum harvest time of apples, the reported Streif Index values are in the range of 0.08-0.3 (Saevels, et al., 2003 & Skic et al.,. 2016). The Streif Index fruit-dependent variable, for example ‘Jonagold’ and ‘Golden Delicious’ show rapid declines in starch content as maturity progresses, which tend to display lower Streif Index values at the time of optimal maturity. Conversely, cultivars exhibiting a more gradual starch conversion such as ‘McIntosh’, ‘Cortland’, Cox's Orange Pippin' and 'Gloster' tend to have higher Streif Index values as the fruit matures (DeLong et al., 1999).

Further, in this study, the changes in Streif Index values during the growing season were significant (ANOVA, $p < 0.05$). Tukey's HSD ($p < 0.05$ and $p < 0.01$) were performed to investigate which week resulted in significant changes as denoted with superscripts in Table 10. Both the week 7 and the week 8 Streif Index values were significantly different from weeks 1 through 4 ($p < 0.01$) and the week 5 ($p < 0.05$), the week 6 Streif Index values were significantly different from weeks 1, 2, and 3 ($p < 0.01$), the week 5 Streif Index values were significantly different from the week 1 ($p < 0.01$) and the week 2 ($p < 0.05$), and weeks 4, 3, and 2 Streif Index value were significantly different from the week 1 ($p < 0.01$), ($p < 0.01$), and $p < 0.01$), respectively. There are no significant changes in Streif Index among the last three weeks ($p > 0.05$), which correspond to the maturation and ripening stages.

Streif Index is a reasonable and consistent descriptor of physiological maturity when the fruit is measured across the latter part of the growing season and during harvest and facilitates the practical utilization of valuable post-storage quality data in determining the suitability for long-term storage (DeLong et al., 199; Streif, 1996; Saevels, et al., 2003). Accordingly, it can be concluded that the anticipated onset of physiological maturation (the week 5) in this study was supported by the Streif Index (0.27), the week 6 Streif Index (0.18) is for harvest time for the long-term storage, the week 7 Streif Index (0.13) is for fresh consumption and the short-term storage, and the week 8 Streif Index (0.09) is immediate consumption and processing.

5.3 Correlations of Thermal Properties and Harvest Fruit Quality and Maturity Indices

To examine if apple's thermal properties change during the growing season is related to the physical property change and the harvest fruit quality and maturity indices change, and correlation among these properties and indices were analyzed. Pearson correlations coefficient (r) values were calculated to test the strength of relationships between apple thermal properties and the properties (density and moisture content) and the harvest fruit quality maturity indices (firmness, soluble solid content, starch index, and Streif Index). Thermal properties were found to have a positive relationship with thermal diffusivity, specific heat, moisture content, firmness, and Streif Index ($p < 0.05$) whereas it has a negative correlation with density, soluble solid content, and starch index ($p < 0.05$). However, the strength of thermal properties with the properties and the harvest fruit quality and maturity indices are mostly moderate or weak based on the correlation coefficient labeling system, i.e., for weak correlations ($0 < |r| \leq 0.35$), for moderate correlations, ($0.35 < |r| \leq 0.67$), strong or high correlations ($0.67 < |r| \leq 1$) or for very high correlations ($|r| \geq 0.9$) (Taylor, 1990).

Among apple's thermal properties, thermal conductivity had a moderate correlation with thermal diffusivity ($r = 0.44$) and moisture content (0.45) while it had a weak correlation with specific heat ($r = 0.27$) and density ($r = -0.04$) (Table 11). Thermal diffusivity had a moderate correlation with specific heat ($r = -0.51$) while it had a weak correlation with density ($r = 0.10$) and moisture content ($r = 0.27$). Specific heat had a strong correlation with density ($r = -0.74$), while it had a weak correlation with moisture content ($r = 0.12$). Because the significance of correlation analyses are less than $p <0.05$, it can be concluded that thermal properties are related to moisture content and density, although the strength of the correlation is moderate or weak. The lack of strength of correlation between apple's thermal properties and the physical properties may be due to inherent biological variances in apple's properties such as biochemical composition and microscopic structure. This is because thermal property of biological materials is affected by cellular structure, density, and moisture (Rahman, 1991; Mohsenin, 1980). The structure of food product also has a major influence on thermal conductivity. For example, parallel fibers in food exhibit different thermal conductivities than perpendicular fibers (Rao et al., 2014). Furthermore, low-density values reduce thermal conductivity due to the void spaces in the product while high-density values of same fruits and vegetables did not significantly increase thermal conductivity (Sweat, 1974). On the other hand, moisture content had a weak negative correlation with density ($r =- 0.17$) in this study, which might be the reason that density of food materials increases with the decrease of the moisture content of food (Rao, et al., 2014).

Further, as listed in Table 11, thermal conductivity had a moderate correlation with all the harvest fruit quality and maturity indices, firmness ($r = 0.44$), soluble solid content ($r = -0.62$), starch index ($r = -0.53$), flesh stain% ($r = 0.44$), and Streif Index ($r = 0.46$). Thermal diffusivity had a moderate correlation with soluble solid content ($r = -0.51$) and starch index ($r = -0.46$), and flesh stain % ($r = 0.37$) while it had a weak correlation with firmness ($r = 0.29$) and Streif Index ($r = 0.27$). On the other hand, the specific heat had a weak correlation with all the harvest fruit quality and maturity indices, firmness (r = 0.31), soluble solid content (r = -0.12), starch index (r = -0.10), flesh stain% (r = 0.09) and Streif Index (r = 0.23). Overall, the correlation between thermal conductivity and the harvest fruit quality maturity indices were higher than those of thermal diffusivity and specific heat.

Besides, the strength of these correlations among the harvest fruit quality and maturity indices were mostly moderate ($0.35 < |r| \leq 0.67$) or strong ($0.67 < |r| \leq 1$). Streif Index had a strong correlation with soluble solid content (r = -0.75), and starch index (r = -0.80), and firmness (r = 0.80), and a moderate correlation with flesh stain% (r = 0.54). Also, firmness had a strong correlation with and starch index (r = -0.73) and a moderate correlation with soluble solid (r = -0.66) and flesh stain% (r = 0.57). Soluble solid content had a strong correlation with starch index (r = 0.86) and flesh stain% (r = -0.68) as expected. Because carbohydrates of climacteric fruit are accumulated in the form of starch in early stage, and they are hydrolyzed into sugars (monosaccharides, mainly glucose and fructose) as the fruit ripens (Salunke 1995, Lin & Walsh, 2008; Thompson, 2015).

Table 11 The Pearson correlations coefficient (r) values among the measured property values and the harvest fruit quality and maturity indices values

Properties	k (W/m-K)	D (mm^2/s)	C_p (kJ/kg-K)	ρ (kg/m^3)	MC (wb %)	Firmness* (N)	SSC (°Brix)	SI (1-8)	Flesh Stain %	Streif Index
k (W/m-K)	1									
D (mm^2/s)	0.44	1								
C_p (kJ/kg-K)	0.27	-0.51	1							
ρ (kg/m^3)	-0.04	0.10	-0.74	1						
MC (wb %)	0.45	0.27	0.12	-0.17	1					
Firmness* (N)	0.44	0.29	0.31	-0.40	0.22	1				
SSC (°Brix)	-0.62	-0.51	-0.12	0.24	-0.70	-0.66	1			
SI (1-8)	-0.53	-0.46	-0.10	0.22	-0.40	-0.73	0.86	1		
Flesh Stain%	0.44	0.37	0.09	-0.17	0.24	0.57	-0.68	-0.82	1	
Streif Index	0.46	0.27	0.23	-0.29	0.45	0.80	-0.75	-0.80	0.54	1

*The firmness at 7.9 mm depth were used. k: thermal conductivity, D: thermal diffusivity, C_p: specific heat, ρ: density, MC: moisture content based on a wet basis (wb%), SSC: soluble solid content, and SI: starch index.

Ferree and Warrington (2003) reported that many maturity indices are imperfect measurements of fruit harvest maturity and are frequently difficult to interpret. The most appropriate maturity indices and desirable values of the maturity indices are specific for each fruit, their cultivars, and use of fruits (Ferree & Warrington, 2003). For example, a biospeckle method, which is a non-destructive method and affected by biochemical changes during the growing season was investigated to determine the optimum harvest time. The Pearson's correlation coefficients between biospeckle activity (BA) and the maturity indices including F, SSC, and SI were moderate (-0.53 and -0.51), (0.63 and 0.40), and (0.43 and 0.44) for 'Ligol' and 'Szampion' apple, respectively. Further, the correlation between F and SI was moderate (-0.67 and -0.67) and the correlation between F and SSC was strong (-0.92 and -0.85) for 'Ligol' and 'Szamoion' apple, respectively. In addition, Streif Index had a strong correlation with F (0.94 and 0.91), SSC (-0.95 and -0.95), and SI (-0.79 and -0.80) while it had a moderate correlation with BA (-0.55 and -0.47) for 'Ligol' and 'Szamoion' apple, respectively. Hence, similar to our study, the biospeckle method was reported as not the sole predictor, i.e., should be supported with destructive methods to predict the optimum harvest time (Skic et al., 2016). Further, dielectric measurements with the non-destructive control method on harvested mature 'Granny Smith' apple were done to find relations with apple physiological compounds such as sugar content or malic acid. The potential use of dielectric spectroscopy for determining the state of fruit maturity was supported with good correlations ($R^2 = 0.84$) between dielectric measurement and Thali index calculated using SSC and acidity. It was reported to try the emerging technology on other climacteric fruit (Castro Giraldez et al., 2010).

Beside biospeckle activity and dielectric property measurements, several non-destructive methods were used to predict firmness, soluble solid content, and starch index of apple during the growing season for indirectly determining the harvest time of fruits. For example, Peng and Lu (2007) used hyperspectral scattering, Qing et al. (2007) used laser light backscattering, Bertone et al., (2012) used Diffuse Reflectance- Ultraviolet- Visible and Near Infrared (DR-UV-Vis and NIR) spectroscopy, and Peirs et al. (2005) used VIS/NIR image. The cross-validation correlation coefficients of firmness and SSC were reported as r = 0.89 and 0.88 for hyperspectral scattering image (Peng & Lu, 2007) and r = 0.90 and r = 0.89 for laser light backscattering image, respectively (Qing et al., 2007), respectively.

In other efforts, an electronic nose was evaluated for predicting the optimal harvest date of ‘Jonagold’ and ‘Braeburn’ apples during the growing season. The quality and maturity indices including firmness, SSC, starch index, acidity, and Streif Index were predicted by the E-nose data (Saevels et al., 2003). Similarly, the cross-validation correlation coefficients (r) were with firmness (0.74 and 0.72), SSC (0.76 and 0.77), starch index (0.80 and 0.76), acidity (0.66 and 0.69), and Streif index (0.89 and 0.92) for ‘Jonagold’ and ‘Braeburn’ apple, respectively. Despite the moderate and strong correlations, disadvantages of this measurement were reported as, slow, not portable, and need for larger sample size.

As mentioned in preceding paragraphs, the maturity indices and several methods are not the sole predictor and are correlated with each other. This study is not only offering the possibility of thermal conductivity property of apple for investigating fruit quality and maturity during the growing season, but it also offers a simple, inexpensive, portable, and rapid method that can be used in lab and orchard. Thus, thermal properties should be checked with other maturity indices besides, SSC, F, and SI. For example, a large increase in internal ethylene production which accompanies the rate of the respiratory peak during ripening is a good indicator of the fruit maturation degree. During the growing season, apple respiration gradually declines until it reaches minimum several weeks before the fruit ripens. Then, the climacteric rise in ethylene production increases the respiration rate once ripening initiates (Salunke, 1995, Castro-Giraldez et al. 2010). Also, starch hydrolysis begins at the end of the fruit development process, around 2–3 weeks before the start of ethylene production, thus close correlation was found between the rate of starch degradation and the ethylene production (Szalay et al., 2013).

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

The property values, i.e., thermal properties, size, density, and moisture content and the harvest fruit quality and maturity indices, i.e., firmness, soluble solid content, starch index, and Streif Index of ‘Gala’ apple cultivar from the FREC in Biglerville, PA during the 2017 growing season were measured. All changes in the values and relationships among all the properties and harvest fruit quality and maturity indices values during the growing season were examined. Thermal properties’ measurement by the DNHP were investigated to predict the harvest time based on their relationships with the harvest fruit quality and maturity indices. Based on this study, the following are the major conclusions.

1) Thermal conductivity and thermal diffusivity of ‘Gala’ apple significantly decreased ($p < 0.01$ and $p < 0.05$), particularly, in the last two weeks of the growing season while specific heat of ‘Gala’ apple did not significantly change ($p > 0.05$) during the growing season.
2) The differences in thermal conductivity values among the apple sides were significant ($p < 0.05$). Hence, the measurement should be done at least at two opposite locations, particularly the darkest and the lightest side of each sample to have a more accurate average value.
3) The density of ‘Gala’ apple was significantly ($p < 0.05$) different between the first and last week while there was no significant difference in ‘Gala’ apple size during the growing season ($p > 0.05$). The moisture content of ‘Gala’ apple significantly decreased ($p < 0.05$), particularly, between the first two weeks and the last two weeks.
4) The firmness, soluble solid content, starch index, flesh stain percentage, and Streif Index of ‘Gala’ apple were significantly different ($p < 0.05$) during the growing season.
5) Thermal conductivity had a moderate correlation ($0.35 < |r| \leq 0.67$) with thermal diffusivity and moisture content, whereas, it had a weak correlation ($|r| \leq 0.35$) with specific heat and density.

6) Thermal conductivity correlations with the harvest fruit quality and maturity indices were higher than those of thermal diffusivity and specific heat. Thermal conductivity had a moderate correlation ($0.35 < |r| \leq 0.67$) with firmness, soluble solid content, starch index, flesh stain percentage, and Streif Index.

Overall, significant changes ($p < 0.05$) in thermal conductivity of apple during the growing season were observed, particularly, in the last week, which corresponded to ripe apple. Simultaneously, significant changes in starch level, soluble solid content, and firmness were observed as well. This study showed the possibility of thermal properties measured by the DNHP for predicting the harvest time. Based on the change in thermal conductivity values during the growing season and correlation with maturity indices, it can be helpful in determining the harvest time but not as the sole predictor.

Recommendations

1) This study should be expanded to find relationships with other apple maturity indices such as internal ethylene content, respiration rate, volatile compounds, organic acid content, etc.
2) Thermal conductivity of different types of apple, other climacteric, and non-climacteric fruits can be investigated to generalize thermal conductivity's capability in predicting the fruit quality and harvest time.
3) The DNHP measurement time can be further reduced to few seconds instead of 60 seconds by decreasing the equilibration time in the beginning and recording time during the measurement.
4) The DNHP probe can be modified to have a different probe length or distance between two probes for fruits with different sizes.
5) The possibility of increasing number of probes can be investigated to take multiple measurements of the specimen at once instead of measuring the specimen two or three times to obatin average values instead of a local value.
6) A simple and nondestructive new method can be developed for thermal property measurement in the orchard.
7) The MATLAB image processing software used for obtaining the starch stain percentage in the core and flesh parts of apple can be improved using additional color components (Green and Blue) for its accuracy and precision.

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RESUME

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Education

- M.S. in Agricultural and Biological Engineering, Pennsylvania State University, University Park, PA. August, 2016 - May, 2018 Current GPA: 3.95
- M.S. in Food Microbiology, Food Engineering Department, Graduate School of Natural and Applied Sciences, Erciyes University, Kayseri, Turkey, September, 2013 – July, 2016. GPA: 3.75
- B.S. in Food Engineering, Faculty of Engineering, Erciyes University, Kayseri, Turkey. September, 2009 – January, 2013. GPA:3.55

Academic Experience

Dissertation and Thesis

- Changes in Thermal Properties During the Growing Season to Predict the Apple Harvest Time and Monitor the Quality **(M.S. Thesis)** in Pennsylvania State University. Advisor: Dr. Virendra Puri.
- Molecular Characterization of Indigenous Lactic Acid Bacteria and Yeasts in Fermented Grape Leaves, July 2016 **(M.S. Thesis)** in Turkey. Advisor: Dr. Ismet Ozturk.
- Physicochemical, Microbiological, and Bioactivity Characteristics of Traditional Home-Made Turkish Vinegars, January 2013 **(Bachelor of Science's Thesis)** in Turkey. Advisors: Drs. Ismet Ozturk and Hasan Yalcin.

Journal Publications

- Ozturk, I., Tornuk, F., **Caliskan-Aydogan, O.,** Durak, M.Z., Sagdic, O. 2016. Decontamination of Iceberg Lettuce by Some Plant Hydrosols, *LWT-Food Science and Technology,* 74, 48-54.

- Ekici, L., Ozturk, I., Karaman, S., **Caliskan, O.,** Tornuk, F., Sagdic, O., Yetim, H. 2015. Effects of black carrot concentrate on textural, bioactive, aroma, color, and sensory properties of sucuk, a traditional Turkish dry-fermented sausage. *LWT- Food Science and Technology,* 62: 718-726.

- Ozturk, I., **Caliskan, O.,** Tornuk, F., Ozcan, N., Yalcin, H., Baslar, M., Sagdic, O. 2015. Antioxidant, antimicrobial, mineral, volatile, physicochemical and microbiological characteristics of traditional home-made Turkish vinegars. *LWT-Food Science and Technology*, 63(1), 144-151.

- Ozturk, I., Karaman, S., Baslar, M., Cam, M., **Caliskan, O.,** Sagdic, O., Yalcin, H. 2014. Aroma, sugar and anthocyanin profile of fruit and seed of Mahlab (Prunus mahaleb L.): Optimization of bioactive compounds extraction by simplex lattice mixture design. *Food Analytical Methods,* 7: 761-773.

Work Experience

Intern

- Dimes Fruit Juice Company, Tokat, Turkey, July-August 2012
- Food Quality and Control Laboratory, Tokat, Turkey, July 2011

Volunteer

- Food Microbiology and Food Chemistry Laboratory, Erciyes University, Kayseri, Turkey, May 2012-Feb 2014.
- Akar Flour Company, Tokat, Turkey, June- July 2010

Scientific Congresses Attended (International)

- NABEC Annual Meeting, Groton, CT, USA, 31 July 2017
- Turkey Innovation Week, Istanbul, Turkey, Nov 2013

- The First Turkish-International Circle’s Workshop on Food Science and Technology, Kayseri, Turkey, May 2013
- Turkey Innovation Week, Istanbul, Turkey, Dec 2012

Certificates

- ISO 9001:2008 Quality Management System (CPA Consultancy Services, 22-24 Dec12)
- ISO 9001:2008 Internal Assessor (CPA Consultancy Services, 22-24 Dec12)
- ISO 22000 Food Safety Management System (CPA Consultancy Services, 22-24 Dec12)
- OHS 18001 Occupational Health and Safety (CPA Consultancy Services, 22-24 Dec12)
- Education of Strategic Management (CPA Consultancy Services, 22-24 Dec12)

Honors, Awards and Memberships

- Turkish Higher Educational Council Scholarship Award for M.S. in the U.S., Jan 2014.
- Graduation; higher rank in the B.Sc., June, 2013.

Membership:

- Institute of Food Technologists (IFT), since Jan 2016.
- American Society of Agricultural and Biological Engineers (ASABE), since May 2017.