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Quantifying the impact of human touch to estimate quality of fresh fruits using light sensing

Master Thesis (30 EAP)

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Abstract

Humans rely on touch and other senses to estimate the quality of fresh fruits and vegetables. While these estimates are subjective from person to person, recent developments in sensor technology have made it possible to estimate fruit quality in a way that is more objective, precise, and accurate.

In the current work, light sensing method was combined with measurements of the firmness of fruit surface by durometer to evaluate freshness of the fruits. The light-sensing method tested and developed here, is based on measurements of the intensities of red, green and blue light reflected from the surface of the fruits.

Our studies showed for all fruit types that reflectivity of red light decreases while fruits are ripening. In case of shorter wavelengths, variation of the reflectivity with time showed its unique fingerprints characteristic to the fruit type.

Firmness of the surface of the fruits studied decreased with time. During a 8- day produce decomposition period, we quantify the impact that human touch has on fresh fruits as quality estimation is continuously performed by customers. Our results suggest that human touch over fresh fruits accelerates their decomposition.

Light sensing offers a non-invasive and cost-effective method to estimate the quality of fresh produce.

CERCS: P170 Computer science, numerical analysis, systems, control

Keywords: optical imaging, light sensing, mobile computing, pervasive computing, produce quality, IoT.

Valgusandurite kasutamine värskete puuviljade kvaliteedi määramiseks ja inimese puudutuse mõju hindamiseks

Kokkuvõte: Värske puu- ja köögiviljade kvaliteedi hindamisel toetuvad inimesed puuviljade puudutamisele ja teistele meeltele. Kuna selline hinnang on subjektiivne, on hakatud kasutama anduritehnoloogiat, et hinnata puuviljade kvaliteeti objektiivsemal ja täpsemal viisil.

Käesolevas töös on puuviljade värskuse hindamiseks kasutatud valgussensorite meetodit kombineerituna puuviljade pinna kõvaduse mõõtmistega durometri abil. Siin testitud ja arendatud valgussensorite meetod seisneb puuvilja pinnalt peegeldunud punase, roheline ja sinise valguse intensiivsuste mõõtmisel.

Uuringud näitasid, et punase valguse peegelduvus puuviljade küpsedes ja riknedes väheneb kõigi puuviljatüüpide puhul. Väiksemate lainepikkuste puhul on igal puuviljatüübil oma iseloomulik peegelduvuse muutumisviis.

Uuritud puuviljade pinna kõvadus aja jooksul vähenes.

Uuritud puuviljade 8-päevase lagunemisperioodi jooksul testisime inimese puudutuse mõju viljade kvaliteedile. Poes välja pandud puuviljade pidev katsumine ostjate poolt kiirendab nende riknemist.

Kasutatud valgussensorite meetod pakub mitteinvasiivset ja odavat võimalust värskete puuviljade kvaliteedi hindamiseks.

CERC: P170 Arvutiteadus, numbriline analüüs, süsteemid, juhtimine

Võtmesõnad: optiline kujutamine, valgustundlik, mobiilne arvutamine, levitatud arvutamine, tooraine kvaliteet, asjade internet (IoT).

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1

Introduction

Food production and agriculture are increasingly harnessing pervasive computing technologies to improve agriculture productivity throughout the supply chain while the main driving force is to improve economic profitability, improved efficiency also serves societal development goals through improved food security and reduced food waste (2). Indeed, the need for improvement in the development of agriculture cannot be far-fetched as the global need for it keeps rising. As we increase production and modernize agriculture, the waste that comes along the production line must be reduced to the barest minimum. Technology advancements, such as sensors, devices, machines, and information technology, have altered how farms and agricultural operations operate today. This same goes for the increase in the waste generally throughout the production supply line. Today's agriculture routinely uses sophisticated technologies such as robots, temperature and moisture sensors, aerial images, and GPS technology.

The quality of fresh produce typically depends on the perception of customers. Even though customers' perception is often linked to manually inspecting the fruits, the quality estimation in this regard is just due to their intuitions and experience. People use all their senses to evaluate quality: sight, smell, taste, touch, and even hearing. The consumer integrates all of those sensory inputs to check the appearance, aroma, flavor, hand-feel, mouth-feel, and chewing sounds into a final judgment of the acceptability of that fruits or vegetables. At the same time, instrumental measurements are preferred over sensory evaluations for many research and commercial applications because instruments reduce variations among individuals, are more precise, and can provide a common language among researchers, industry, and consumers. However, the relation-

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ship of the instrumental measurement to sensory attributes (e.g., descriptive analysis) and the relationship of those sensory attributes to consumer acceptability must be considered (3). Instruments may be designed to imitate human testing methods or may be statistically related to human perceptions and judgments to predict quality categories. Essentially, appearance is detected instrumentally by measuring electromagnetic (usually optical) properties, texture, mechanical properties, and flavor (taste and aroma) by chemical properties. Some sensors are based on signals not detectable by humans e.g near-infrared, X-ray, magnetic resonance and electrochemical (3). Methods such as human touch (manual visual inspection), automated image processing (4) and different form of spectral imaging (5) are difficult to adopt as they either support only specific stages of the supply chain or are expensive and difficult to operate. In addition, these techniques are expensive and difficult to use as off-the-shelf solutions, requiring deploying sophisticated devices. To overcome these limitations, solutions that are low-cost and easy to deploy are required (2, 6, 7).

In this thesis, we aim to present an innovative and low-cost method for characterizing different organic produce using reflective green, red, and blue light sensing. Our solution re-purposes inexpensive and widely available (RGB) light sensors to analyze superficial changes in the produce caused due to their decomposition over time.

Light sensors are very essential in determining the quality of fruits throughout the supply chain which includes planting, growing and cultivation, processing, grading and packaging, storage, bulk transport and distribution, retailers and consumers, and waste (8). However, we focus on the last supply chain: retailers, consumers, and waste. Once the produce reaches the retailers, it enters the last supply chain phase, where the produce is sold, consumed and/or disposed. Here, retailers can use wearables and sensors integrated into fruit stalls to support product inventory management and to dynamically determine best-before dates (9). Similarly, consumers can use personal wearables and baskets integrating light sensors to determine the quality of produce during purchase and consumption phases.

Our solution only requires a single point of contact to obtain a coarse-grained estimation of the quality of produce. As demonstrated by existing work in which this work is inspired (2), our solution can support different use cases in the produce supply chain. To evaluate our method, we rely on a M5 smart controller, which has a small resolution

LCD screen with Wifi, which transfers the RGB light sensor to the fruits, and its readings are generated. Also, a durometer (as gold standard) which serves as baseline for your experiment is used to measure the firmness of the fruit (quality indicator). This durometer is pressed on the fruits to check the hardness and establish a baseline for changes on the surface of the produce. Through a rigorous analysis that considers eight consecutive days, we demonstrate how changes on the produce surface are accelerated by human touch. We conducted a user study with 15-20 participants who touch the fruits and simulate like they are at the store trying to buy their favorite fruits. This experiment shows that human touch can have an effect on the quality of the fruits.

1.1 Contributions

The following sums up the contributions of this work:

- **Method:** We develop a novel sensing approach to analyze the damage human touch has on the decomposition of organic produce (fruits) using a light sensor and the hardness of the organic produce using durometer.
- **Insights:** We present an innovative and low-cost method for characterizing different organic produce (fruits) using light sensing. Our solution re-purposes inexpensive and widely available green, red, and blue light sensors while only requiring us to put this produce centimetre away to provide insights about the quality factors.
- **Improved performance:** We perform rigorous experiments demonstrating that human touch significantly affects the quality of the organic produce compared to the untouched organic produce.

1.2 Outline

This thesis is structured as follows:

- Chapter 2 reviews the existing approaches for fruit quality estimation which includes manual inspection and chemical analysis and a state-of-the-art light sensing device. Moreover, we also demonstrate how firmness of fruits are tested using durometer as baseline. Lastly, we discuss the effect of human touch on fruit decomposition.

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- Chapter 3 describes the M5 light sensor and the Red, Green and Blue (RGB) light sensor experiment.
- Chapter 4 describes the experimental setup for this experiment and also demonstrates how the optical light sensor is used in this work to determine the organic produce decomposition and how durometer is used to check the hardness and also the fruit selection, participants, and data collection.
- Chapter 5 describes the result, findings, and analysis of the light sensors and the durometer and their comparison.
- Chapter 6 discusses the implications and limitations of our work.
- Chapter 7 presents the summary and conclusion of our work.

2

State of the Art

2.1 Existing approaches and experiment for fruit quality estimation (Baselines)

This research presents an approach on how to check for fruit quality, especially the off-the-shelf produces. There have been several existing approaches for quality estimation. First, visual inspection is a simple and cheap method where fruit quality is assessed by visual inspection of external characteristics such as color, shape, size, and skin condition. However, it is subjective and may vary based on the experience and expertise of the inspector. It is a traditional way of estimating the quality of fruits however the challenges and its limitations are due to its laborious nature as well as inconsistency in the inspection and classification process (10). The tasks of grading and sorting of fruits according to their outer appearance and freshness are still laborious and challenging in nature at the level of small-scale enterprises. The manual quality control highly depends on the trained humans to inspect the outer appearance of the fruits and then decide about their grading (10).

Another existing approach is mechanical testing which involves measuring the physical properties of the fruit, such as firmness, which is an important indicator of fruit quality. It can be measured using devices such as durometer, penetrometers or texture analyzers (11). However, it has its own limitations, the overall quality of the fruit especially the internal quality such as ripeness and flavor cannot be accessed accurately. Other limitations include sensitivity to moisture content may affect the reading and fruit with delicate skins can be easily be affected by the durometer.

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Other existing approach for fruit quality estimations is chemical analysis. Chemical analysis has been known to be used in determining the quality of fruits as it provides information about the various chemical constituents present in the fruits. This analysis also determines the nutritional value, ripeness, maturity, and overall quality of fruits. Examples of chemical analysis include testing the moisture content of the fruits by drying a known weight of the material in an oven at a specific temperature, testing the pH which is the degree of acidity or alkalinity of the fruits, total phenolic content (concentration of phenolic compounds which contribute to antioxidant activity and quality of the fruits) and mineral analysis test (12). However, its limitations include time consuming process, limited scope and some parameters such as sugar content, acidity or vitamin level do not provide the picture of fruit quality, which is influenced by various factors such as taste, texture, aroma and overall sensory experience.

2.2 Light Sensing

This chapter reviews light sensors and material sensing which is the groundwork of this thesis and presents an overview of recent research that we consider relevant for this study. From the aforementioned material sensing, we will be using light sensors to acquire data on the qualities of the fruits chosen for this thesis. We will be focusing on RGB (red, green, and blue) light sources and sensors and using them to estimate the quality of the fruits. Employing non destructive sensing techniques such as light sensing in the fruits industry assure preservation of the quality and wholesomeness of fruit after the quality control. This would increase consumer satisfaction and acceptance and enhance industry competitiveness and profitability.

Various non-destructive sensing techniques have been studied and implemented for predicting the quality of fresh fruits for instance, light-based sensing techniques offer great prospects for measuring the firmness and sugar or soluble solids content (SSC) of fruits. The interaction between radiation and matter has been proven useful in many research labs. Ultraviolet (10-400nm), Visible (400–750nm) and Near Infrared (750–2500 nm) (UV-VIS-NIR) spectroscopy are gaining increased attention in the field of post-harvest quality assessment of fruits (6).

A light sensor device, also known as a light sensor or a photodetector, is an electronic component or device that detects and measures the intensity or presence of light.

Sensor devices are used in various applications including electronics, industrial automation, healthcare, and agriculture. These devices are capable of sensing, computation, and communicating, they are generally composed of low-power radios, several smart sensors, and embedded CPUs (Central Processing Units) (13). A Light Dependent Resistor is one of the example of a sensor (LDR). Active and passive sensors are the two different categories of sensor equipment. In contrast to passive sensors, which only detect and react to some form of input from the physical world, active sensors are sensing devices that need an external source of electricity to function. Also, a typical example of a sensor device is spectroscopy. Spectroscopy is the analysis of matter and its interaction with electromagnetic radiations (14), and a spectral signature is the variation of reflectance or emittance of a material with respect to wavelengths. The application of visible (Vis; 400–750 nm) and near-infrared red (NIR; 750–2500 nm) region spectroscopy to assess fruit and vegetables is reviewed in context of ‘point’ spectroscopy, as opposed to multi- or hyperspectral imaging (15).

Near-infrared spectroscopy is a physical method for the non-destructive determination of mostly organic molecular compounds (16). NIR spectroscopy works with light between approximately 800 and 2,500 nanometers wavelength and thus lies between the visible spectral range (VIS) and the mid-infrared (IR). A major benefit of NIR spectroscopy is that it doesn’t need any sample preparation. This method can be used to do analysis of the soil, disease and pest detection. NIR technology offers advantages such as rapid results, and the ability to analyze multiple parameters simultaneously. It enables efficient decision-making in agricultural practices, enhances crop productivity, and supports sustainable farming approaches.

Hyperspectral imaging (HSI) is an emerging field in which the advantages of optical spectroscopy as an analytical tool are combined with two-dimensional object visualization obtained by optical imaging (17). The usage of spectral sensing may open an avenue in post-harvest and food processing for fast, high-throughput assessments of mechanical and biochemical of fruits (18). Advantages of using HSI in agriculture are its non destructive method, less time consuming and no sample preparation is required like chemical analysis. However, it has some limitations such as variability in fruit samples (color, size maturity and shape) affect the accuracy, complexity, and cost, limited spectral range and limited applicability.

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2.2.1 Computer imaging for fruit quality estimation

The automated quality assessment of fruit images by computer vision is commonplace in the post-harvest supply chain and is typically used for sorting and grading (19). Grading is the classification according to several quality attributes such as color, size, or defects (20). They provide several advantages for pack house operators and retailers in the food supply chain. First, damaged or off-spec fresh produce is sorted out, fruits can also be packed better if they are sorted based on size, for example, in trays or boxes. In addition, grading of fruits and vegetables into different categories based on quality at harvest enables producers to sell their products in different price ranges for the different grades based on consumers' needs. In case of limited cooling capacity, producers can also choose to store only high-value products in cold storage. Automated sorting and grading have largely replaced manual quality estimation for fresh produce in high-income countries due to its increased efficiency and reduced labor cost. At the same time, algorithm based solutions establish a common standard for visual inspection and remove human bias (20). Computer imaging using a camera involves capturing visual information from the real world and converting it into digital data that can be processed and analyzed by a computer. Cameras used in computer imaging typically consist of a lens system, an image sensor, and various electronics for image capture and processing. However, image processing and analysis can be computationally intensive, requiring powerful hardware and processing time. Also, they are heavily influenced by ambient light conditions and may not capture more than the visual characteristics of fruits.

2.2.2 Material sensing

Each material may be recognized by its individual fingerprint, these fingerprints can be seen using spectroscopy. With the help of technology, a material may be identified and its conditions and quality can be determined. To identify the material or material composition, the sensor needs to learn which spectrum belongs to which material. Therefore, calibration must be performed where the software program relates reference values to measured spectra.

The most popular method of material sensing uses several light spectrum components and evaluates either reflection or absorption at various frequencies for example, the green light sensor was used to determine the quality of ripe and unripe fruits (8).

In this work, We shall focus on using three colours - red, green and blue light (RGB). We shall measure the light intensity using RGB sensors, and study how the intensity varies with time and ripening of the fruits. The light sensor data can be used for quality estimation.

Employing non-destructive sensing techniques in fruit industry assure the quality and wholesomeness of fruit. Various non-destructive sensing techniques have been studied and implemented for predicting the internal quality of fresh fruits. Its principle of estimating this fruit quality is that of light reflectivity which will be explained in our next chapter.

2.2.3 Principle of light scattering and reflectivity

Deep insight into the basics of scattering theory and understanding the peculiar features of electromagnetic/light scattering is essential for modern technology (21). Scattering refers to the phenomenon where light waves encounter particles or irregularities in a medium and change their direction of propagation. When light interacts with small particles or structures that are smaller than the wavelength of light, such as dust particles, molecules, or small droplets, scattering occurs while reflectivity refers to the ability of a surface or material to reflect light.

When light encounters a surface, it can be either absorbed, transmitted through the material, or reflected back. Reflectivity is a measure of how much light is reflected compared to the incident light. The reflectivity of a material depends on various factors, including the nature of the material, its surface properties, and the wavelength of light. It is often characterized by the reflectance spectrum, which describes how the reflectivity of a material varies with different wavelengths of light. Measurements of the amount of light scattered or reflected by the surface of fruits have been used to estimate the quality of the fruits. The reflectivity, or reflectance, of fruits can provide valuable information about their physical and optical properties, such as color, texture, and surface characteristics. This principle is commonly utilized in fruit quality assessment, sorting, and grading processes Figure 2.1 explains how the principle of light scattering and reflectivity works (1).

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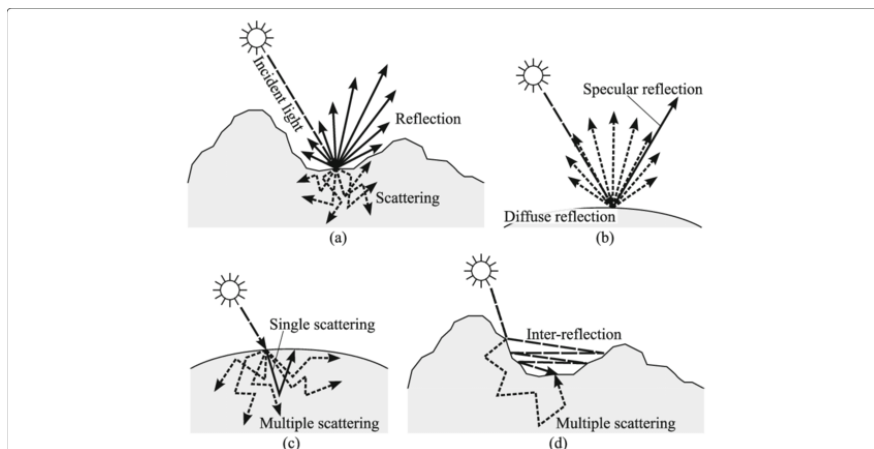


Figure 2.1: Light reflection and scattering. (a) reflection and scattering phenomena at a point. (b) reflection is classified into two components: diffuse and specular reflection. (c) scattering is also classified into two components: single and multiple scattering. (d) inter-reflections and multiple-scattering phenomena are similarly based on multi-bounce collisions (1)

2.3 Firmness and Durometer (Baseline)

Firmness refers to the material's resistance to deformation or compression under an applied force. It describes the material's ability to maintain its shape and structural integrity when subjected to pressure. Firmness is often associated with the material's elasticity or stiffness while hardness on the other hand refers to a material's resistance to scratching, indentation, or abrasion. A durometer is a measurement tool used to assess the hardness or firmness of materials such as rubber, coatings and plastics and fruits. To test the firmness of organic material, which is fruits here, we will make use of a durometer. Durometer has long been used in checking the hardness of several materials, including fruits for example, fruit firmness was measured manually using a durometer (Shore Durometer Hardness Type 0-2, Shore Instrument and Mfg. Co., Jamaica, N.Y.) fitted with a 2.4-mm-diameter hemispherical probe (22). Firmness of the fruits refers to the softness or hardness of the produce and it is commonly used as an indicator of ripeness (23). As the durometer, we used the commercial fruit hardness tester (53215 series) which has a measuring capacity of 90 shore. The durometer is non-invasive due to its small tip size (5mm and 2.38mm), and it can be used for a wide range of produce. The durometer probe was pressed against the fruit tissue in a single smooth motion

2.3 Firmness and Durometer (Baseline)

over 1 to 2 s and the maximum reading recorded (22).

In the case of fruits such as apples, pears, and peaches, durometers are commonly used to measure the force required to penetrate the fruit's skin. This measurement can help determine the fruit's maturity level, with riper fruits requiring less force to penetrate. By using a durometer to measure fruit hardness, producers and sellers can better assess the quality of their produce and make informed decisions on when to harvest and sell their fruits. Other than visual appearance, the most important factor in fruit quality is firmness. Fruits quality is influenced by the hardness of the epidermis, the firmness and the internal structure of the fruit, which vary widely among cultivars like in the case of tomato (24). The durometer can also be used to measure the firmness of fruits such as strawberries, mango, blueberries, and grapes. In this case, the durometer measures the force required to compress the fruit slightly, giving an indication of its firmness and ripeness. However, for this project, we will be using durometer on various fruits to test the firmness which in turn give idea about how good the quality of the fruits are. The hardness or firmness test is done by manually via physical touch of the tip of the durometer to the marked part of the selected fruits, the tests can be done in a vertical and horizontal position of the selected fruits. Below is the Figure 2.2 of the durometer used to test the firmness of fruits.

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Figure 2.2: Durometer used for the experiment.

2.4 Effect of human touch on fruit decomposition

Overall, recent studies have suggested that the effect of human touch on fruit decomposition can vary depending on various factors, such as the type of fruits, the ripeness of the fruits, and the force of the touch. Depending on a few variables, including the type of fruits, the amount of pressure used, and the time spent in contact, human touch can have either beneficial or harmful impacts on fruits. Gentle human contact can help soft fruits like avocados and tomatoes mature evenly and produce a better flavor. Gentle handling can help remove any dirt or debris on the surface and improve the appearance of firm fruits like apples and pears. Some fruits, like kiwis and mangos, may also benefit from gentle handling pressure that helps to soften and make them more palatable. However, fruits like peaches, plums, and berries can suffer bruises or other skin damage from excessive pressure or rough handling, which can shorten their shelf life and cause spoiling. Some fruits, like grapes and bananas, are more prone to bruising than others and should be handled carefully to prevent tearing the skin and hastening to ripen. If the fruit is not thoroughly washed before ingestion, contact with human hands may also spread germs or other contaminants to its surface, increasing the risk of deterioration or foodborne illness. Also, the thermal properties of fruits determine the rate of its decomposition, fruit thermal conductivity values ranged between 0.13 and $0.89 \text{ Wm}^{-1}\text{K}^{-1}$, an average of $0.53 \text{ Wm}^{-1} \text{ K}^{-1}$ while specific heat values of whole fruit ranged from 1.72 to $4.05 \text{ kJkg}^{-1}\text{K}^{-1}$ with an average value of $3.74 \text{ kJkg}^{-1}\text{K}^{-1}$.

Fruits with high water content generally have higher specific heat. Melons used

for this work have an average specific heat capacity of $4.05 \text{ kJkg}^{-1} \text{ K}^{-1}$ (25). Similar to specific heat capacity, fruit with high moisture content have higher values of thermal conductivity. This is attributed to the higher thermal conductivity of water compared to other fruit contents (26), (27).

2.5 Summary

In this chapter, we presented light sensing and evaluation of firmness of fruits using durometer. Also, we presented existing approaches such as visual inspection and chemical analysis with their limitations.

Furthermore, we explore the various light sensing for fruit quality such as hyperspectral imaging, near infrared spectroscopy, computer imaging for fruit quality estimation and its limitations. *"Unlike the previous work, we study the impact that human touch has on the decomposition of fruits using the reflective light sensing RGB model to analyze the quality of the fruits."* To evaluate whether the reflective light sensing which produces red, green and light can be also used to determine the fruit quality decomposition, in the next chapter, we introduce M5 light sensor and its working principle.

3

Device for Light Sensing

This Chapter describes the light sensing method for organic produce characterization and its quality estimation using inexpensive and widely available RGB sensors to provide insights about the quality factors while only requiring a single point-of-contact.

3.1 M5 Light sensing device

Huber Flores et al have built an optimized device that embeds the light sensors connected to a computing board for carrying out the analysis of values. The device uses a wireless M5StickC PLUS ESP32 development board that controls the sampling frequency of the light sensor and uploads the samples to a centralized server (28). The M5StickC Plus contains an inbuilt Wi-Fi connection facility, battery supplies (120 mAh @ 3.7V), and an LCD screen to externalize the activities of the board. Moreover, it is lightweight (21g) and portable, such that it can be flexible to deploy (65 mm $\times$ 25 mm $\times$ 15 mm). The device takes light measurements using an RGB LED diode (5mm in size, 0.06W power draw) and a photo-resistor (5M Ω) (28). The photoresistor measures the intensity of light reflected back from the beam produced by the LED diode. The photoresistor captures analog voltage measurements, which are converted to digital voltage representations. The output value of ADC (analog to digital conversion, with 12-bit resolution) is used as the physical unit for reflected light intensity. Our design exploits the principle of light scattering and reflectivity to evaluate the produce quality. To connect the development board and the sensor, female-to-male jumper wires were used to connect each color pin to a digital pin on the M5StickC PLUS and this was

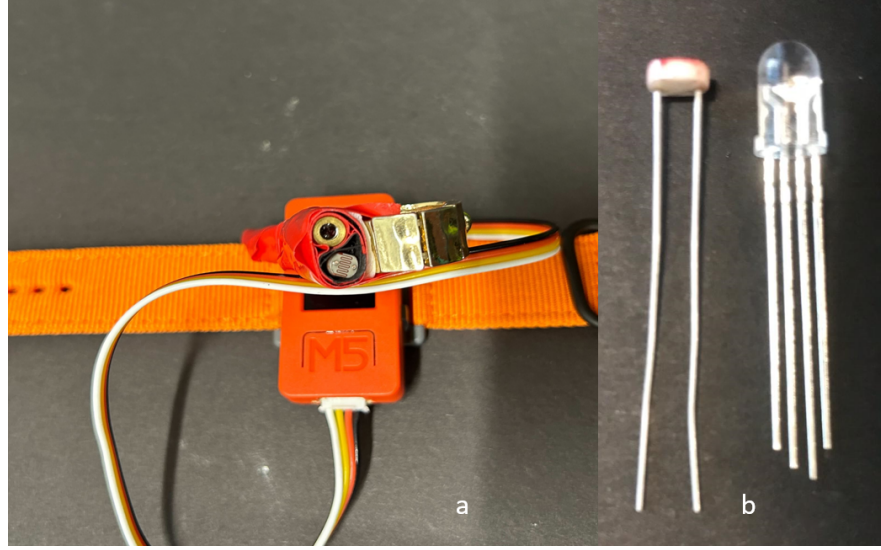


Figure 3.1: Design of the (a) Light sensor, (b) Photo resistor and RGB LED

put together by an expert in the research group. Once the RGB sensor has been connected to the board, the value for each colours can be uploaded to the web server (java enabled software). These light intensity values can then be used to evaluate the fruit quality. These values are measured in lux (symbolized lx) is the unit of illuminance in the International System of Units (SI). It is defined in terms of one lumen per meter squared (lm/m^2).Our design is shown in Figure 3.1

3.1.1 RGB model

Real color sensors from the M5 light sensor are built on the widely used RGB model (red, green, blue). Red, green, and blue light are all part of the visible light spectrum and are associated with different wavelengths. These three colors have distinct characteristics. Red light has the longest wavelength approximately 620-750 nanometers (nm) and is associated with low energy while green light with wavelength 495-570 nm is associated with moderate energy and blue light with wavelength 450-495 nm is associated with higher energy. These three fundamental hues can be combined to produce a significant portion of the visible spectrum. For multiple-color sorting, several color sensors can detect multiple color applications (29). For categorization and identification tasks, a sensor may be designed to recognize simply one color or a variety of color kinds or shades, depending on how challenging the task is. This application has

3. DEVICE FOR LIGHT SENSING

been widely used for example in the grading of organic produce like bananas, grading is a vital process during the post-harvest of horticultural products as it dramatically affects consumer preference and satisfaction when goods reach the market. Manual grading is time-consuming, uneconomical, and potentially destructive. A non-invasive automated system for export-quality banana tiers was developed, which utilized RGB, hyperspectral imaging, and deep learning techniques(30). Using an RGB light sensor offers several advantages over using a camera by its low-cost choice, simplicity, it shows real-time measurements of fruits quality and firmness, it can quickly capture data without the need for image processing, making them suitable for high-speed applications and timely decision making. Also, RGB light sensor captures non-visual characteristics of fruits such as color, reflectance, and transmittance which in turn provide valuable insights into fruits quality and ripeness. They are also less sensitive to ambient lighting variations which makes it reliable in different lighting environments and it does not involve complex computational tasks.

3.2 Summary

This chapter presented the setup and design of the light sensor (M5 Stick C Plus) to be used in the analysis of the organic produce. Light sensors can be used to estimate fruit quality by measuring the amount and distribution of light reflected by the fruit's surface. This can provide valuable information about the fruit's maturity, ripeness, and overall quality. Light sensors can further be used in estimating fruit quality such as color measurement, surface defects detection, and maturity estimation.

4

Experimental Setup

This Chapter discusses the protocol used in the user experiment i.e. how the whole experiment is set up, and describes the experimental test bed designed to show the effect of manual physical inspection on produce quality by three visible light colors (red, green, blue). Also, the durometer which serves as baseline is used to check the hardness of the produce as a gold standard.

4.1 Produce

We consider five different fresh produce that are commonly available in a supermarket and that cover all 5 main categories of produce: pepo (melon), pome (pear), berry (banana), drupe (mango) and hesperidium (lemon) (8). They were all purchased fresh and of the same quality at a supermarket same day in October (late autumn season) and we consider two items of each fruit produce S1 (touched) and S2 (untouched). Thus, in total 10 fruits are used in the experiment.

4.2 Testbed

Two types of measurements were carried out on one testbed: light sensing and surface hardness measurements. To carefully manage how the light sensors are positioned in relation to the materials (fruits), we set up a controlled testbed for obtaining measurements. The experimental set up for the light sensor is shown in Figure 4.1a. A black surface with location marks is part of our arrangement. All samples are evaluated

4. EXPERIMENTAL SETUP

roughly in the same region and from the same location thanks to the fixed markers, while noise from potential backdrop reflections is avoided by using a dark surface.

The sampled fruit (touch or untouched) is then placed 1 centimeter away from the light sensor to achieve the most accurate results (8). The light ray was perpendicular to the surface of the fruit samples. The RGB sensor detects light intensity in three specific wavelength regions namely red (600-700 nanometers), green (500-600 nanometers) and blue (400-500 nanometers), when the light which is generated from the Light Emitting Diodes (LED) enters the sensors, the photoresistor measures the intensity of light in its respective wavelength regions, the sensor then converts these light intensities into electrical signals, usually represented as digital values. The output data from the sensor which corresponding to the intensity of the detected light in the red, green and blue regions are then used to determine the fruit produce quality. This measurement is done twice on two marked location on the fruit surface to achieve the best result.

To minimize the effect of background, the light intensity for the ambient condition were also measured using a LUX light meter application for android devices throughout the 8 days of measurement. We further used light intensity value to determine the variation in the quality of both the touched and untouched fruits.

In addition to light sensing, hardness of the fruits was also measured using durometer. The durometer which is the baseline is pressed against the surface of the fruits thrice and the durometer automatically calculates the average and this is recorded for the 8 days of the experiment. The experimental set up for the durometer are shown in Figure 4.1b.

4.3 Survey design and Participants

For each measurement day, we recruited 20 different participants who were new to the the experiment. In total, 158 participants (76 males and 82 females) were recruited, ranging in age from 17 to 51 (25.49 ± 6.54). The participants were university students, staff and also the researcher’s social circle from different fields and nationalities.

We ran an on-site survey on produce quality assessment. The evaluation took place in the same university building but at different locations for 8 days. Completing the survey took on average 5 minutes for each participant. Responses were elicited on a five-point Likert-scale (anchored at 5: strongly agree and 1: strongly disagree). Participation

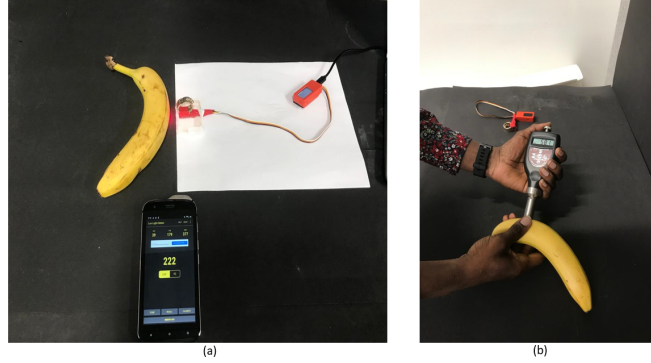


Figure 4.1: Experimental test bed with fixed black background to avoid noise from surrounding objects; (a) Light intensity measurement at fixed distance to the fruit and lux meter application (running in a smartphone) to capture luminosity of ambient conditions (b) Durometer pressed against the fruit (baseline)

in the survey was anonymous and voluntary. The qualitative and quantitative analysis from the questionnaire were filled, question statement for each produce quality estimation is like: *"Is the banana of a good quality to eat?"*. Overall, the survey included 6 questions in a closed-ended questionnaire format. Besides, additional open-ended questions were included to elicit additional feedback about the survey (e.g., *"What is your strategy for estimating fruit quality?"* and *"What quality attribute motivates participants to buy fruits?"*). The question format is shown in Figure 8.2

We conducted the experiment for 8 consecutive days. For each measurement day, we showed all the fruits with sample 1 in a plastic basket to the participants. Participants are allowed to tap, touch and smell each fruit for 10 seconds. This simulates the normal interactions with the produce when consumers go to the grocery. Then the participants rank the fruits and finish the survey.

4.4 Sensing data collection

After the survey, we used a test bed to obtain clean measurements of all the values needed to determine the quality of the fruits after each day of the experiment. The sensing device uploads the data to a web server (a java application) via WiFi and two random 1-minute measurements per fruit (touched fruits S1 and untouched fruits S2) for each light colour are taken to mitigate the potential biases. The LUX values throughout the 8 days were very stable and consistent. Also, the ambient light intensity were

4. EXPERIMENTAL SETUP

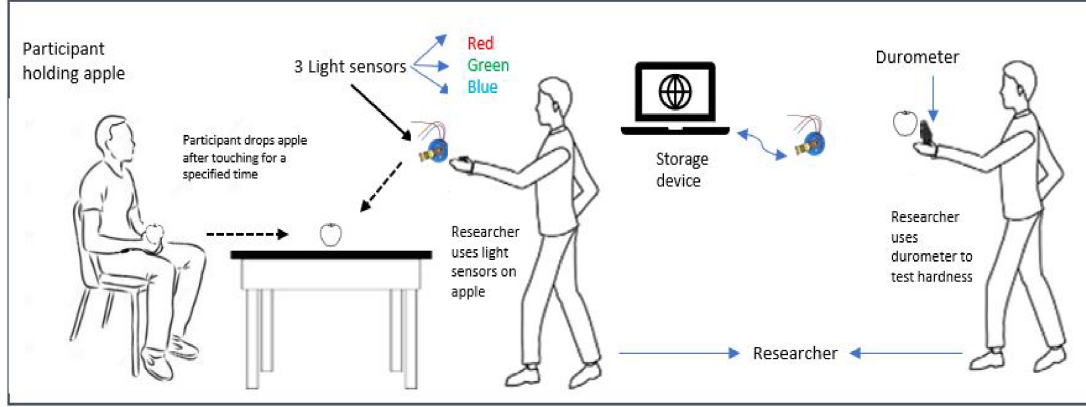


Figure 4.2: Participant interacting with the fruit, researcher using light sensor to test the quality of fruits, researcher using durometer to test the firmness of the fruit

measured using the LUX light meter for android and it was done for the 8 days during the measurement. After that, we use durometer to record the firmness (ground truth) for each produce. To get the accurate ground truth, the durometer measured 3 different marked surface of each fruit (both the untouched and touched) (30 measurements) and the durometer is set automatically to get the average value and this was recorded. Lastly, a picture of the touched and untouched produce was taken at the end of the experiment.

4.5 Summary

In this chapter, we discussed the selection of fruits for this experiment, the study design which includes the survey design, participants simulate how they check quality of fruits at a supermarket and its corresponding research questions with fruit quality ranking to them. Also, how the test bed was set up to ensure the accuracy of our results was discussed here plus the way the experiment was conducted. We also explain how durometer (gold standard) is used to determine the firmness of the fruits selected for quality estimation.

5

Results and Analysis

This Chapter discusses the results and the analysis of the data gotten from light sensor experiment. Here, we compared the values from the red, green and blue light used on both the touched and untouched organic produce on a day-to-day basics. Also, the analysis done by durometer on the touched and untouched fruits is analyzed here.

5.1 Day by day coarse-grain analysis

We first demonstrate that human touch can affect the produce quality by camera images. Figure 5.1 shows the appearance changes for these fruits of eight days. We can see that there have been no significant changes in appearance for all fruits in the first 3 days, except for some black spots in the touched banana. From day-4, compared to the untouched one and other fruits, the touched banana started to decompose first with more small brown spots and speckles. Then it became black and shrunken faster. Besides, the touched pear also shows apparent external changes earlier than the untouched one, especially after day-5 with a large browning area and fluid from the damaged part. Similar to these results, other touched fruits (e.g. lemon, mango and melon) also accelerated degradation with more and darker spots as well as rougher textures. Thus, we can roughly see that human touch can accelerate fruit decomposition and reduce fruit quality. Human touch can introduce microorganisms (e.g. fungi and bacteria) to the fruits, and some can break down organic produce. In addition, human touch could unintentionally bruise and damage the fruit's skin. Damaged areas are more susceptible to microbial colonization and enzymatic degradation, leading to faster decay.

5. RESULTS AND ANALYSIS

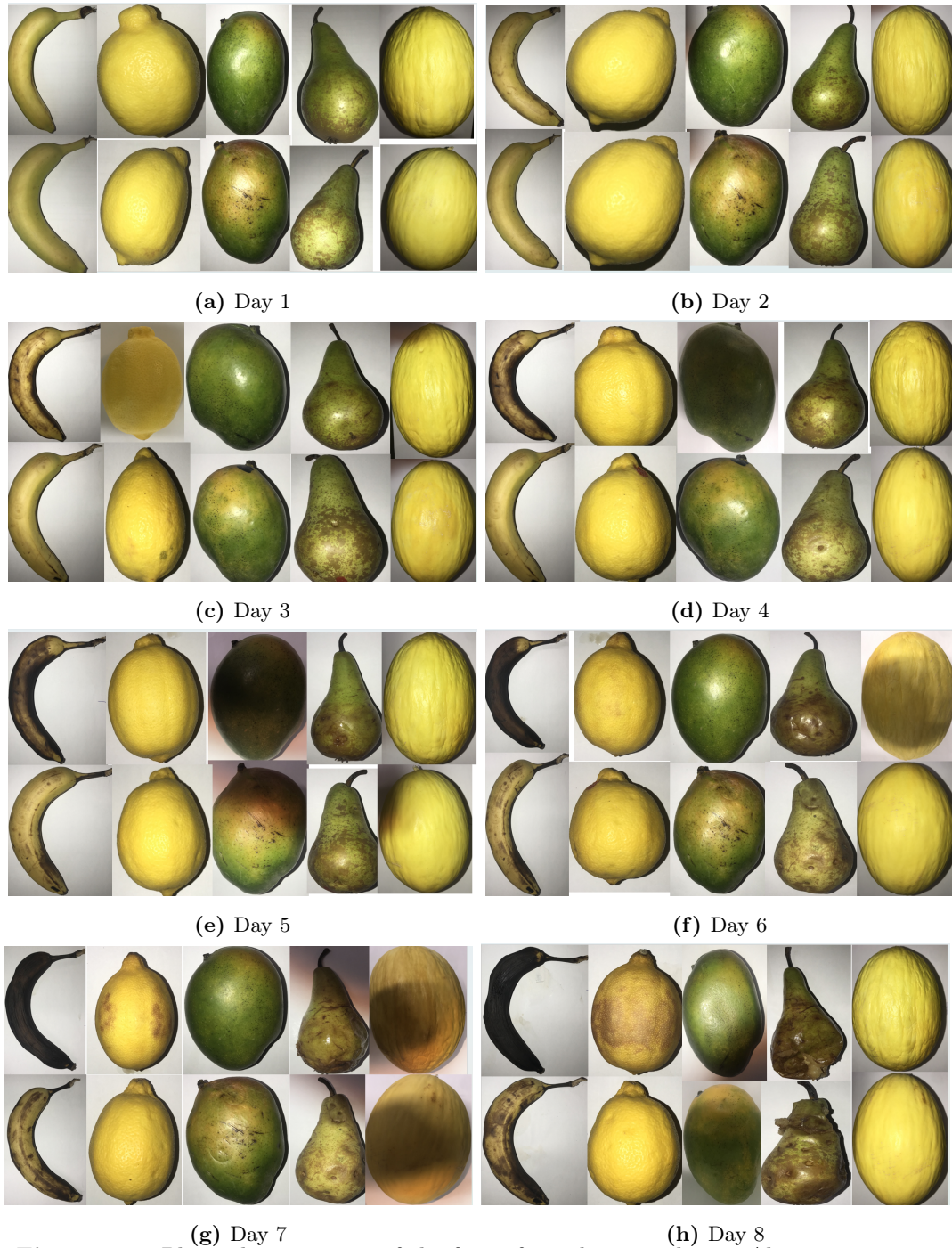


Figure 5.1: Physical appearance of the fruits from day 1 to day 8. Above pictures are fruits sample 1 (touched (upper)) and fruits sample 2 (untouched (lower)) in each day.

5.2 Durometer analysis (Baseline)

Fruits	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8
Touched banana	54	57	50.6	39.3	37.7	20	10.5	5.5
Untouched banana	52.4	49.3	61.3	49.3	53.4	46.7	44.3	36.7
Touched mango	59.5	49	49.7	46.1	21.7	20.1	11.2	10.1
Untouched mango	54.5	47	53.9	48	43.4	46.6	49.8	30
Touched pear	51.6	41.1	43.1	32.9	37.9	21.9	17	17.1
Untouched pear	42.7	49.2	45.4	50.4	43.1	47.1	38.3	27.6
Touched lemon	53.5	50.1	46	50.5	42	51.6	53.6	49.4
Untouched lemon	58.5	58.5	53.2	58	59.7	51.3	50.2	53.1
Touched melon	78.7	78.9	78.4	74	71.4	74.8	68.7	69.3
Untouched melon	83.6	85.8	88	76	81.2	83.1	80.2	79

Table 5.1: Firmness captured by durometer for each produce (scale: 10-90 shore)

5.2 Durometer analysis (Baseline)

To quantify the effect of decomposition over time, we collected baseline measurements from two different items of each fruit type: sample 1 is the touched fruit and sample 2 is the untouched sample. Figures 5.2 to 5.6 shows the results of the firmness data measured by durometer. The numerical data are in the Table 5.1.

It can be clearly seen from the Figures 5.2 to 5.6 that firmness of touched fruits decreases more rapidly. From these measurements, we can observe that firmness of all touched fruits begins to decrease drastically from the 3rd day, especially in case of

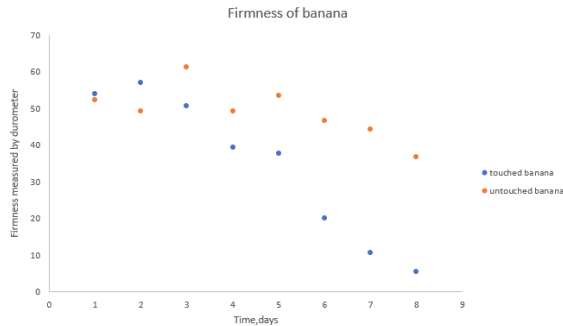


Figure 5.2: Firmness captured by durometer for banana over 8 days.

5. RESULTS AND ANALYSIS

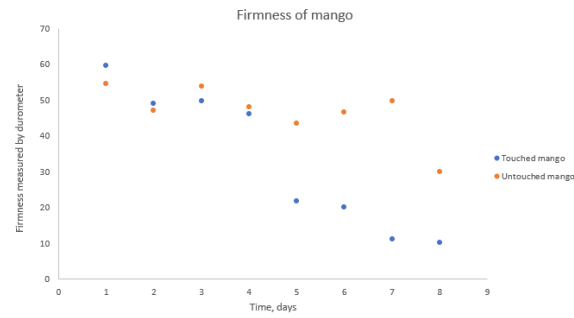


Figure 5.3: Firmness captured by durometer for mango over 8 days.

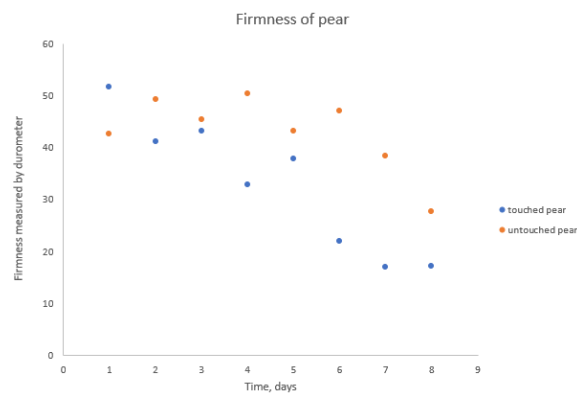


Figure 5.4: Firmness captured by durometer for pear over 8 days.

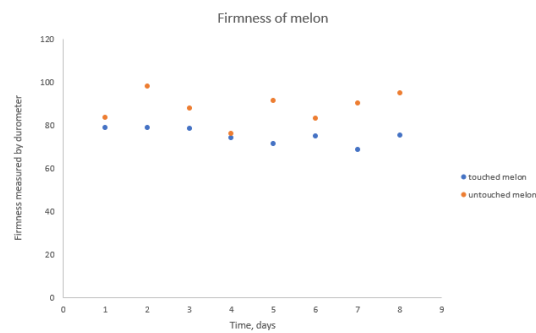


Figure 5.5: Firmness captured by durometer for melon over 8 days.

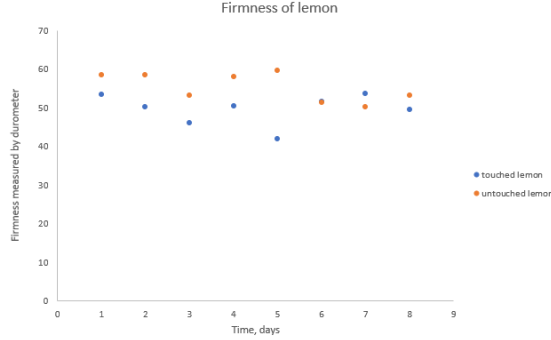


Figure 5.6: Firmness captured by durometer for lemon over 8 days.

banana, mango and pear. The peel of melon is thicker and harder, which can lead to a weaker effect of human touch than these 3 fruits. But we can still observe the difference between melon-1(touched) and melon-2 (untouched). Unlike decomposition with a decreased tendency in firmness, the value in the touched lemon first decreased but increased after 5 days. The reason is that the peel gets harder during decomposition. However, we can still observe that human touch hastened the decomposition of the lemon compared to the untouched one. Wilcoxon rank tests also separately verified that there were statistically significant differences between the two samples of each produce (banana: $\chi^2 = 3, p < .05$, mango: $\chi^2 = 6, p < .05$, mango: $\chi^2 = 4, p < .05$, lemon: $\chi^2 = 3, p < .05$ and melon: $\chi^2 = 0, p < .05$).

5.3 RGB sensor measurements

Illumination (luminous flux per unit area) of the fruit surface was measured using the RGB sensor device. The intensity of the reflected light is proportional to the illumination measured in lux (lx). The light intensity and its variation with time measured across different types of fruits is an unique fingerprint for each group of fruits. We performed measurements for 2 sets of 5 different fruits (1 is touched and 2 is untouched) and measurements for each different fruits are collected during the same day for 8 days.

The results of RGB sensor measurements are presented in Tables 5.2 to 5.7. Each illumination value was measured 2 times and the mean value and its standard deviation are shown in the Tables 5.2, 5.4, 5.6 , 5.3, 5.5 and 5.7.

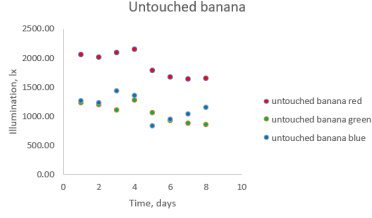
5. RESULTS AND ANALYSIS

Kruskal-Wallis tests using the light values also show the differences to be significant for all the fruits where χ^2 is Chi-square which measures the extent to which the ranks of observations among different light colour differ from what would be expected under the assumption of no differences between the light colours., η^2 is eta-squared which represents the proportion of the total variability in the dependent variable (i.e. the outcome being measured) that can be attributed to the differences between the light colours and p is the p-value less than the predetermined significance level (typically 0.05) which suggests that the differences between the light colours are statistically significant, indicating that at least one light colour differs significantly from the others (Blue: $\chi^2 = 45.72$, $\eta^2 = 0.61$, $p < .05$, Green: $\chi^2 = 38.30$, $\eta^2 = 0.52$, $p < .05$, and Red: $\chi^2 = 46.29$, $\eta^2 = 0.63$, $p < .05$). Pairwise post-hoc comparisons (Dunn-Bonferroni) for the light values indicated significant differences in all but three cases: Blue (banana-lemon: $\chi^2 = -0.10$, $p > .05$ and mango-melon: $\chi^2 = 0.08$, $p > .05$), Green (banana-pear: $\chi^2 = -1.35$, $p > .05$ and mango-melon: $\chi^2 = 1.57$, $p > .05$), and Red (banana-pear: $\chi^2 = -0.03$, $p > .05$). This result indicates that different light colours can generally distinguish between different produce, but still struggles with specific produce.

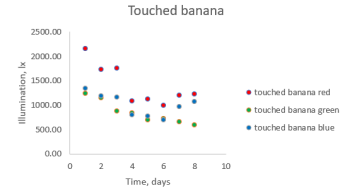
To improve the characterization performance, it is better to observe separately different colours as each produce has different photosensitive properties. For example, all these fruits can absorb more blue and green light but reflect more red light, thus increasing the red light intensity of reflectivity. As seen from Figure 5.7, reflected red light intensity is much higher than the intensity of reflected green and blue light. We can also see that illumination decreases in time whereas the decrease is remarkably more rapid for the touched fruit.

Figures 5.8, 5.9 and 5.10 demonstrate variation of reflected light intensity separately for each sensor colour. We can observe different behaviour for different colours and different fruits. In case of reflected red light, the intensity decreases with ripening for all fruits. The intensity for the touched fruit is smaller for banana, mango and pear, while for lemon and melon there is almost no difference between touched and untouched fruits. The intensity of reflected green light also decreases with time and difference between touched and untouched fruits depends on the fruit. For banana, the intensity is remarkably smaller for touched fruit, but for other fruits, the difference of green light intensity of touched and untouched fruits is small. The intensity of reflected green light from touched fruits can even be higher than the intensity of light reflected from untouched

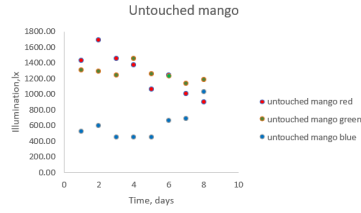
5.3 RGB sensor measurements



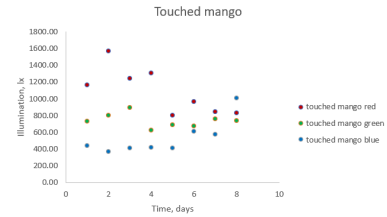
(a) Untouched Banana



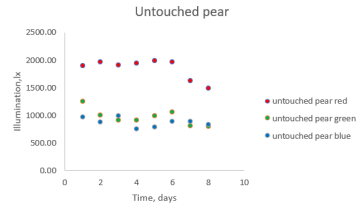
(b) Touched Banana



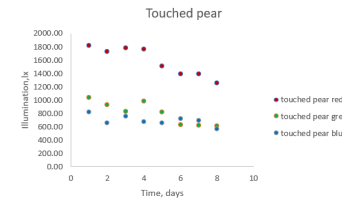
(c) Untouched Mango



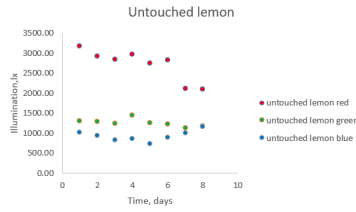
(d) Touched Mango



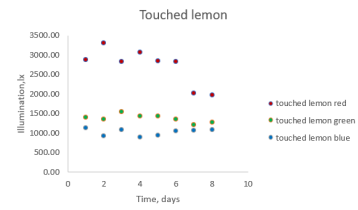
(e) Untouched Pear



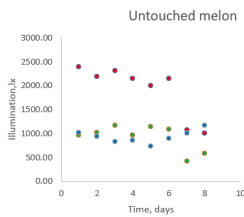
(f) Touched Pear



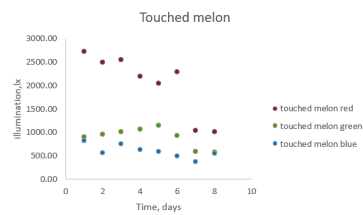
(g) Untouched Lemon



(h) Touched Lemon



(i) Untouched melon



(j) Touched melon

Figure 5.7: Comparing the the reflected light intensity over the 8 days for the touched and untouched fruits

5. RESULTS AND ANALYSIS

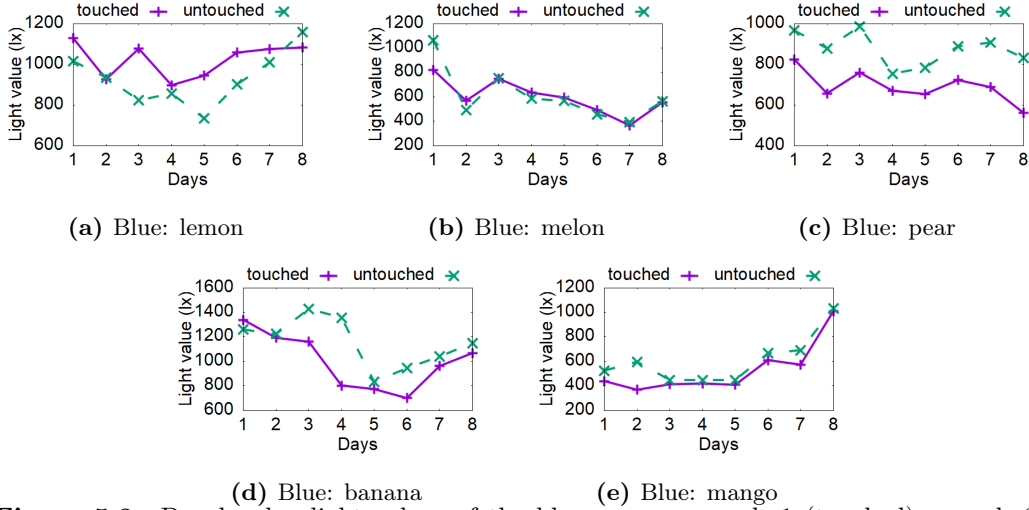


Figure 5.8: Day by day light values of the blue sensor: sample-1 (touched), sample-2 (untouched)

fruits. In case of blue light, the intensity is remarkably smaller for touched fruits like banana, mango and pear i.e. the intensity of reflected blue light begins to increase as from day 2 for banana, pear and mango till the last day for the untouched compared to the touched fruits, while for lemon and melon, the difference between touched and untouched is insignificant, each fruit has its characteristic behaviour of variation of these intensities and it is determined by the structure of the fruits. The standard deviation of light for the touched fruits are higher compared to how the untouched fruits are. However, from the figures shown, it was observed that lemon has higher light intensity value (lx) which shows that the decomposition of lemon was exhibited with the thicker skin of it.

The accuracy of the measurements when our RGB sensor device is used, is not very high as one can see from the data presented in the figures and the tables and the values of the standard deviations. However, the trend that reflectance of red and green light decreases when the fruits are ripening can be clearly seen. Thus, we can conclude that ripening of the fruits decreases the reflectivity of the surface of the fruits for all the visible light wavelengths. It can be explained with the changes in the structure of fruits while ripening. On the other hand, when one possesses the reflectivity data, or illumination data measured by RGB sensor device for a certain fruit depending on the fruit's freshness, he can use this dependence to evaluate freshness of a fruit.

5.3 RGB sensor measurements

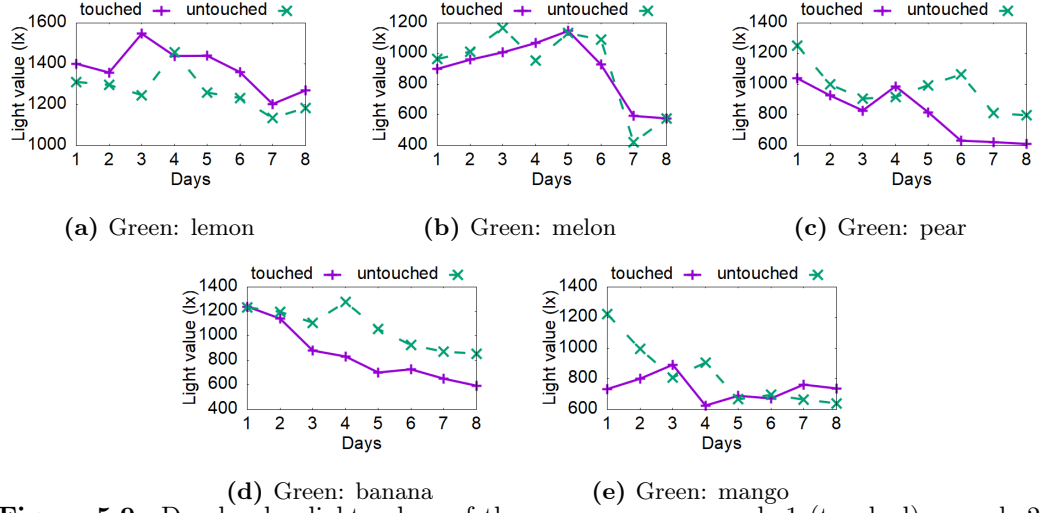


Figure 5.9: Day by day light values of the green sensor: sample-1 (touched), sample-2 (untouched)

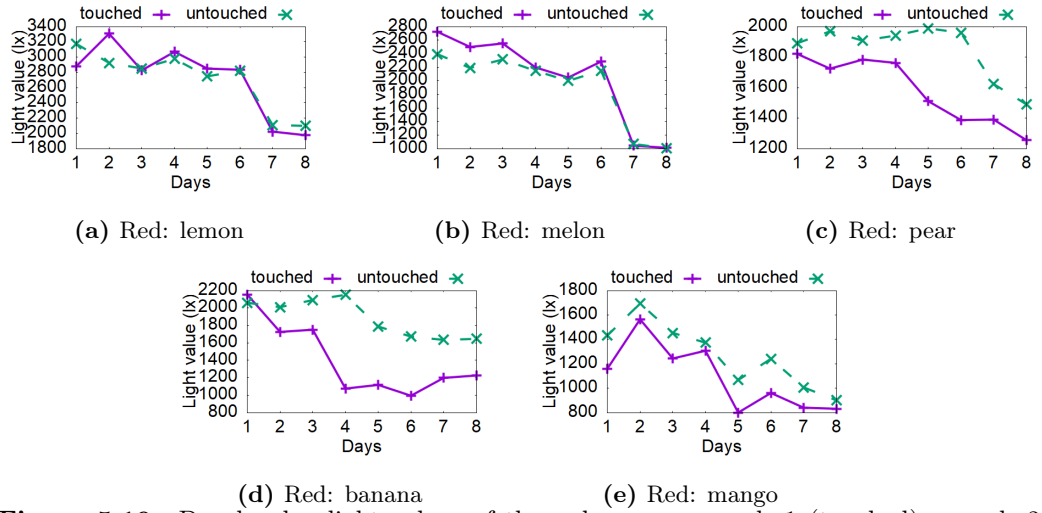


Figure 5.10: Day by day light values of the red sensor: sample-1 (touched), sample-2 (untouched)

5. RESULTS AND ANALYSIS

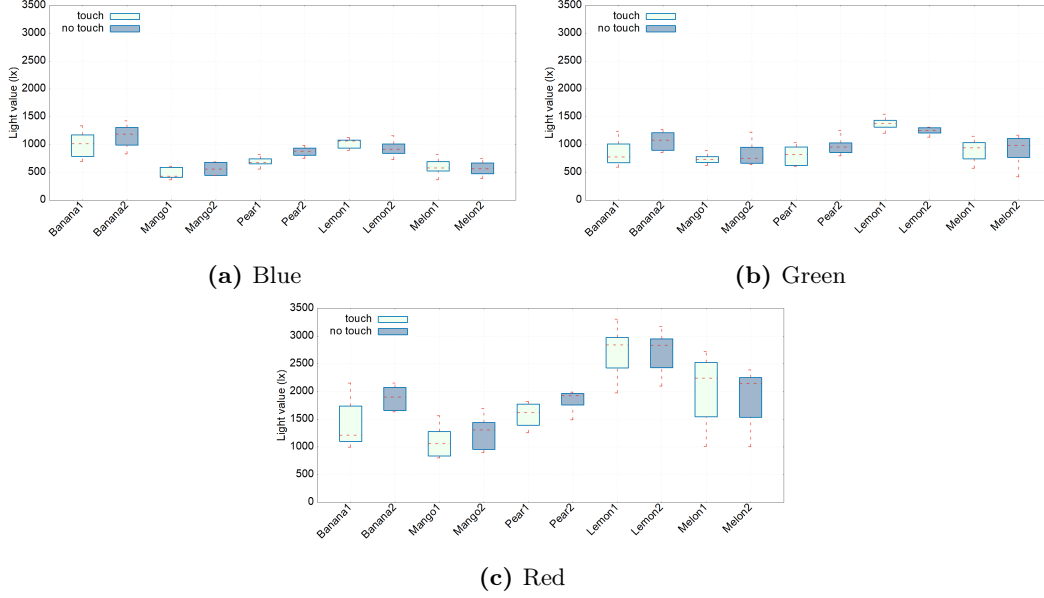


Figure 5.11: Light intensity values measured in lux (luminous flux per unit area) of the three colours

Our tests showed that the standard deviation of light i.e the increased in variability or dispersion of the light intensity values around the mean of the touched fruits are higher compared to that of the untouched fruits. It can be related to damage the human touch have done to it which cause the rapid decrease in the light intensity value after 8 days. From the figures shown, it was observed that lemon has higher reflected light intensity value (lx) which shows that the decomposition of lemon was exhibited with the thicker skin of it. In that way, each type of fruit has its specific properties.

5.4 Capturing produce quality

We next demonstrate that our approach can estimate produce quality. Figure 5.8, 5.9 and 5.10 show the results of different light colors over the 8 days. Similar to the ground truth captured by durometer, we can observe a decreased tendency for light values in the red sensor for most fruits, followed by the green sensor. These figures show the day by day differences between the light intensity values (lx) of the touched and untouched fruits. This indicates that light sensing can capture the fruit quality as a function of decomposition. Wilcoxon-signed rank test using the two periods (day

1-4, day 5-8) as experimental conditions also showed that differences in light values are statistically significant across all fruits (Red: $Z = 739, r = 0.69, p < .05$, Green: $Z = 687, r = 0.69, p < .05$), except the blue sensing ($p > .05$). Although light values in the green sensor can capture the produce quality within the two periods, the observed values in pear and banana from Figure 5.9 (c-d) exhibit a fluctuating pattern with no predominant upward or downward movement. Red light can capture the fruit quality better than the other two, but data in mango displays a lack of clear directional trend. However, the utilization of blue sensing in mango has demonstrated potential for enhancing produce quality estimation, exhibiting an upward trend from Figure 5.8(e). The ambient light conditions were seen to be relatively stable across the 8 days of measurement as shown in Figure 5.12. Also, the mean and the standard deviation of the light sensor used in the estimating the quality of touched and the untouched fruits were presented in Tables 5.2, 5.4, 5.6, 5.3, 5.5 and 5.7. Upon observing the mean and standard deviation tables for the fruit samples, the mean light values for touched fruits indicates relatively lower values compared to untouched light values. This can be attributed to surface deformations and light blockage due to contamination of surfaces, the presence of such irregularities can contribute to reduced light intensity measurements for touched fruits. Also, it become evident that the standard deviation for touched fruits exhibit slightly higher values compared to the untouched tables. This can also be attributed to the rapid surface changes that take place when the fruit is touched, and this trend persists across different colors of light. Additionally, touching a fruit may induce slight deformations on its surface as explained earlier and these deformations can create areas of differential light transmission or absorption, leading to localized variations in the intensity of light detected by the sensor. Generally, it is expected that all standard deviations will decrease in value in the later days as fruits decompose and undergo visible color changes across larger surface areas, as observed in the standard deviation measurements from day 5 to day 8 of the experiments.

5.5 Effect of human touch

We next analyze whether light sensing can be used to capture the effect of human touch on produce. FigureS 5.8 to 5.10 still show the results of touched and untouched samples for each produce. We can observe that the difference between samples can be captured

5. RESULTS AND ANALYSIS

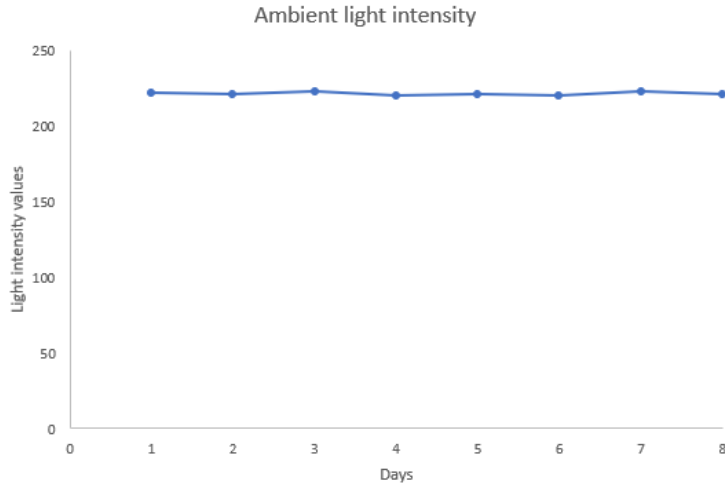


Figure 5.12: Average ambient light intensity values across the 8 days. Indoor environment in which the testbed was deployed showed to be produce a stable ambient luminosity.

Touched Fruits										
	Banana		mango		pear		lemon		melon	
Days	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD
Day 1	2153.00	30.05	1159.31	14.64	1820.29	23.13	2879.95	30.86	2722.98	34.89
Day 2	1725.70	10.20	1564.38	11.58	1724.08	27.70	3306.96	23.84	2499.16	20.72
Day 3	1750.90	23.02	1243.61	23.05	1783.52	20.86	2825.99	35.15	2550.36	30.13
Day 4	1075.96	12.16	1306.86	9.40	1761.78	15.67	3069.42	24.10	2197.47	17.07
Day 5	1117.78	8.47	800.29	7.03	1510.99	9.45	2849.29	20.28	2047.52	16.91
Day 6	993.51	8.88	960.81	14.47	1387.23	12.54	2833.65	16.91	2282.79	14.28
Day 7	800.51	9.19	840.34	6.76	1390.16	9.55	2022.62	13.32	1043.71	6.87
Day 8	753.36	7.58	831.27	8.68	1255.68	9.83	1975.49	12.61	1011.60	6.24

Table 5.2: Mean and standard deviation of the light intensity values (lx) of the touched fruits over the 8 days using red light.

5.5 Effect of human touch

Untouched Fruits										
Days	Banana		mango		pear		lemon		melon	
	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD
Day 1	2059.61	26.19	1431.51	15.21	1891.01	20.75	3172.25	27.11	2392.84	25.32
Day 2	2009.98	12.93	1693.81	13.60	1968.55	12.50	2924.13	23.66	2189.72	14.55
Day 3	2090.96	13.89	1453.03	10.25	1907.71	22.09	2850.40	33.49	2314.49	26.45
Day 4	2151.18	13.04	1372.48	9.49	1940.66	11.41	2976.61	24.46	2147.46	17.07
Day 5	1787.44	12.65	1066.71	7.89	1988.32	13.88	2747.01	17.09	1998.82	10.22
Day 6	1672.20	11.60	1241.18	18.81	1959.04	14.69	2822.23	16.10	2149.75	13.79
Day 7	1634.07	10.15	1006.66	6.46	1623.29	10.84	2110.01	12.54	1066.88	9.05
Day 8	1646.00	7.00	900.64	5.79	1490.22	9.86	2097.94	8.60	1006.34	4.73

Table 5.3: Mean and standard deviation values of the light intensity values (lx) of the untouched fruits over the 8 days using red light.

Touched Fruits										
Days	Banana		mango		pear		lemon		melon	
	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD
Day 1	1238.0	16.5	732.6	6.0	1037.2	17.6	1399.2	21.0	899.0	15.0
Day 2	1140.4	25.7	799.8	13.0	925.4	8.0	1356.3	16.9	958.9	8.2
Day 3	879.4	27.2	891.1	6.2	827.3	6.6	1546.1	11.4	1006.9	7.4
Day 4	831.3	13.1	625.0	4.7	985.4	13.0	1437.2	13.8	1067.0	10.8
Day 5	700.7	5.3	688.6	4.7	816.3	5.0	1438.4	21.2	1146.4	11.8
Day 6	726.6	7.4	671.4	12.2	630.7	5.4	1358.3	16.0	927.4	7.5
Day 7	650.4	6.7	761.1	5.7	621.4	4.7	1202.4	8.3	592.0	4.4
Day 8	593.3	5.4	736.5	5.2	609.3	4.7	1268.5	7.0	575.9	3.7

Table 5.4: Mean and standard deviation values of the light intensity values (lx) of the touched fruits over the 8 days using green light.

5. RESULTS AND ANALYSIS

Untouched Fruits

Days	Banana		mango		pear		lemon		melon	
	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD
Day 1	1232.2	18.5	1310.4	6.5	1251.2	18.0	1310.4	18.5	963.2	19.2
Day 2	1195.4	11.3	1295.8	12.9	997.2	7.2	1295.8	11.3	1011.1	9.6
Day 3	1107.3	6.9	1246.1	6.4	905.5	6.4	1246.1	6.9	1166.3	8.1
Day 4	1274.4	18.8	1455.1	8.2	915.0	11.5	1455.1	18.8	955.0	8.7
Day 5	1054.5	9.9	1258.4	5.5	992.8	4.3	1258.4	9.9	1132.0	6.8
Day 6	925.1	6.6	1231.9	5.6	1062.1	4.4	1231.9	6.6	1089.3	5.1
Day 7	870.6	7.5	1133.6	5.7	810.3	6.0	1133.6	7.5	419.4	4.6
Day 8	854.7	8.8	1183.2	5.6	796.3	3.2	1183.2	8.8	576.5	5.2

Table 5.5: Mean and standard deviation values of the light intensity values (lx) of the untouched fruits over the 8 days using green light.

Touched Fruits

Days	Banana		mango		pear		lemon		melon	
	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD
Day 1	1338.8	19.2	439.0	5.4	823.0	13.7	1127.6	19.7	820.7	25.8
Day 2	1191.3	26.0	368.1	3.2	656.9	6.2	926.2	25.5	567.8	10.7
Day 3	1159.9	8.3	412.7	4.1	759.4	6.7	1076.4	6.9	748.0	11.6
Day 4	803.1	10.2	419.4	5.1	669.6	5.7	897.2	6.4	634.6	5.6
Day 5	773.0	6.1	408.4	4.2	653.5	4.3	944.0	7.3	593.4	3.9
Day 6	700.1	5.8	609.7	11.0	722.0	4.5	1057.0	13.8	492.4	4.4
Day 7	661.9	8.3	572.9	5.4	687.5	5.0	1075.1	7.3	365.6	4.1
Day 8	558.9	7.2	561.8	4.5	561.5	4.7	1082.1	6.8	553.6	3.9

Table 5.6: Mean and standard deviation values of the light intensity values (lx) of the touched fruits over the 8 days using blue light.

5.6 Comparism of both durometer and light sensing studies

Untouched Fruits										
	Banana		mango		pear		lemon		melon	
Days	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD
Day 1	1258.8	17.1	524.6	5.7	966.1	16.6	1014.7	16.7	1063.0	18.1
Day 2	1222.9	17.9	596.2	6.7	878.1	8.4	935.0	17.9	490.5	7.5
Day 3	1427.3	9.4	447.8	5.0	986.1	8.4	823.0	5.7	752.0	6.5
Day 4	1356.8	10.8	447.4	5.6	754.0	5.6	856.3	7.6	585.2	5.2
Day 5	832.2	6.9	447.5	5.5	783.4	8.6	734.2	5.8	565.5	3.8
Day 6	944.6	6.9	665.4	5.4	888.3	7.5	900.6	16.6	456.5	5.6
Day 7	1039.5	4.8	691.0	4.8	906.5	6.3	1008.4	7.1	392.6	6.4
Day 8	1149.7	6.4	1032.4	4.0	831.6	5.7	1158.7	6.3	564.1	5.5

Table 5.7: Mean and standard deviation values of the light intensity values (lx) of the untouched fruits over the 8 days using blue light.

by a combination of the three light colors, e.g. blue sensing in lemon, pear and banana; green sensing in banana and pear; red sensing in pear, banana and mango. Wilcoxon-signed rank test using the two samples for these produce also validated this observation ($p < 0.05$). The only exception is melon without a significant difference between the samples ($p > 0.05$). The limited variation in appearance during decomposition and the presence of a robust peel serve as contributing factors that can account for the diminished effects of human touch on the produce. Overall, our methodology can successfully capture the comprehensive impact of human touch on the fruit, incorporating a combination of different light colors.

5.6 Comparism of both durometer and light sensing studies

After collecting values from both the baseline durometer measured and light sensing approach and normalizing the data, a comparison was made to identify any similarities in the trends. The baseline durometer measurements provided an initial reference point for assessing the firmness of the fruit hence quality, while the light sensing approach captured variations in light intensity associated with the fruit surface properties. Upon analysis, it was found that the two approaches exhibited similar trends after normalizing the light intensity values (less than 3500 lx) and durometer values (10- 90) shore to be of the same value between 0 and 1. This implies that there is a correlation between the

5. RESULTS AND ANALYSIS

	Banana		mango		melon		pear		lemon	
Days	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD
Day 1	4.35	0.59	3.50	0.76	3.30	0.76	4.15	0.93	4.25	0.85
Day 2	3.88	0.93	3.59	1.00	3.47	1.07	2.94	1.25	3.29	1.31
Day 3	3.46	0.99	3.96	1.08	3.50	0.99	2.12	0.95	3.23	1.27
Day 4	3.05	1.00	3.95	0.83	3.80	0.89	2.20	1.11	3.60	0.88
Day 5	3.00	1.08	3.83	0.79	3.33	0.91	1.39	0.61	3.39	0.92
Day 6	2.21	0.98	3.79	0.85	3.37	1.01	1.84	1.01	2.95	0.71
Day 7	1.65	0.93	3.10	1.02	3.30	1.22	1.25	0.44	2.25	0.85
Day 8	1.20	0.52	1.90	0.79	2.45	1.10	1.10	0.31	1.70	0.80

Table 5.8: Mean and standard deviation values of the fruit quality rank by participants.

firmness of fruits, as determined by the durometer, and the light intensity detected by the light sensing approach. The observed similarities in trends suggest that the light sensing approach could potentially serve as a reliable alternative or complementary method to assess fruit quality. Figure 5.13 shows the comparison as seen with touched fruits

5.7 Survey

In this experiment, we asked our participants (both male and female) to touch and simulate like they are in the store trying to buy their favourite fruit produces and how they check it with their touch, feel it and use their experiences to check how good the fruits produce are. Each day, 15 -20 participants are called upon (students, lecturers and other participants of different fields and nationalities). They had little or no knowledge about optical light sensing, as there was no such prerequisite. After each day of the fruits produce been touched by the participant, each participant ranked the quality of the fruits on the scale of 1-5 which serves as the quantitative analysis by the participant and questions were asked which as the qualitative analysis as shown in Figure 8.2. The mean value and mean standard deviation (SD) from day 1 to 8 were presented in the Table 5.8.

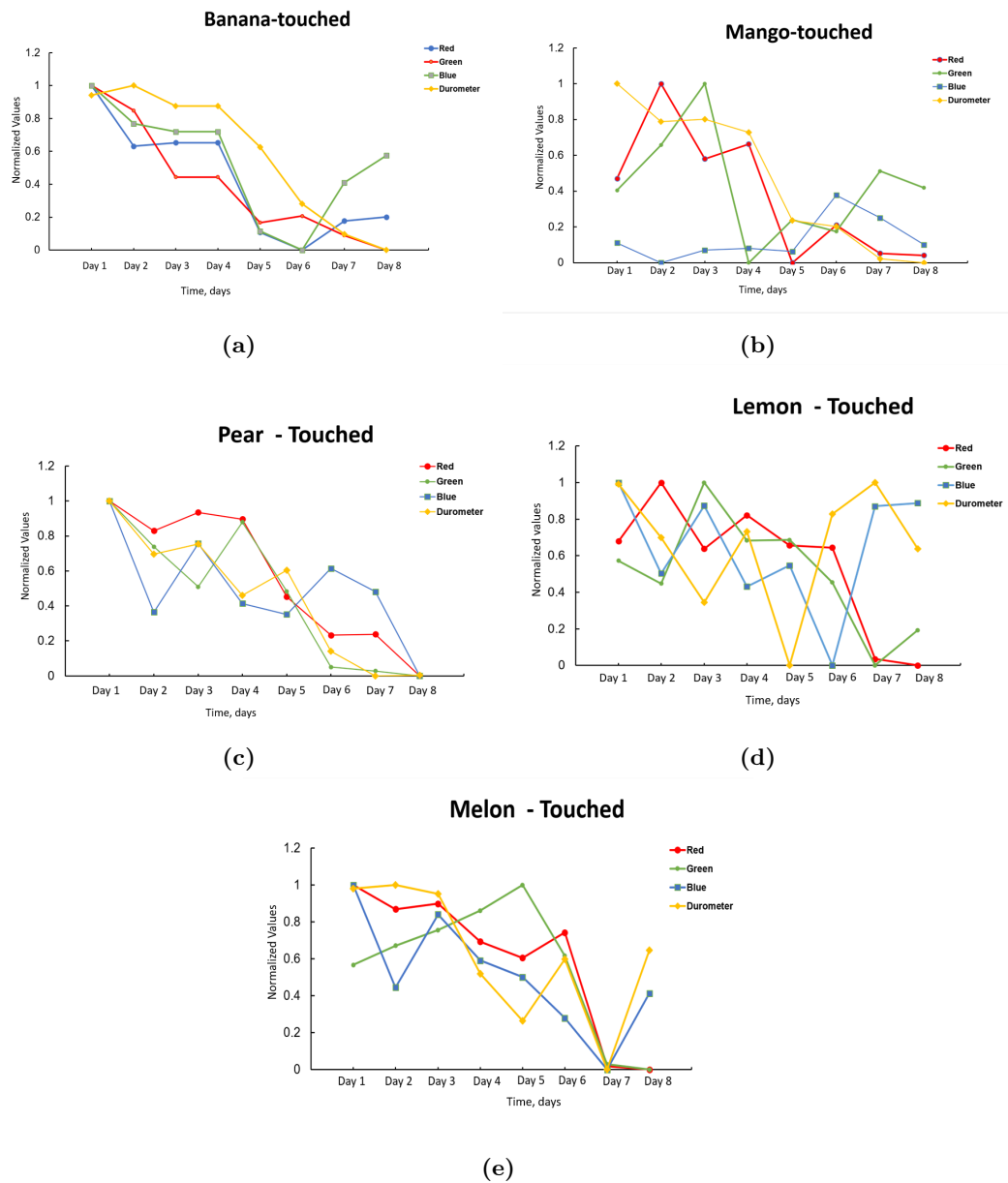


Figure 5.13: Comparing the baseline(durometer) with the light sensor.

5. RESULTS AND ANALYSIS

5.8 Summary

In this Chapter, we started by showing the day to day analysis of the fruits using the blue, green and red (RGB) light sensor and the differences in the quality of the touched and untouched fruits were clearly seen. We then explain the results gotten from the durometer and light analysis which serves as baseline using tables, figures, and statistical data. Furthermore, the effect of human touch were so evident after the analysis has been done on the touched one by comparing the durometer(gold standard) and the RGB light sensor data by the way they follow same trend throughout the 8 days of this experiment. From the quality rank of the participants, we were able to generate the mean and its wide variation between the first day of the experiment when the fruits were still good and the last day, when it had deteriorated.

6

Discussion

This Chapter discusses the implications and limitations of our work.

6.0.1 Accuracy and cheap hardware

We rely on an MD5 micro controller and low-cost sensors to develop our device. While other hardware solutions could be utilized in our device (Raspberry pi or Arduino and laser diodes), data collected by rapid and low-cost sensors is known to be very inaccurate and quite volatile (31). This means even the same sensors (from the same vendor and type) could present high variations in data collection. As a result, in this thesis, we are interested to look at the trends which can be modelled and monitored by these devices. To make the results comparable between devices, it is thus required to develop calibration models that compensate for the inaccuracies of low-cost hardware.

6.1 Human touch

Human touch has been proven to cause damage to the organic produce in this case fruits in our work. The average temperature of human touch falls within a narrow range around normal body temperature, which is typically around 37 degrees Celsius (98.6 degrees Fahrenheit) which shows that gradual transfer of heat from the palm to the fruits gradually deteriorate the fruits as observed. Also, with the touch, we can have a sense of their texture and firmness. Human touch can introduce bacteria and other contaminants to the surface of the fruits which can gradually increase the rate of decomposition of the fruits. Fruits with soft, thin and delicate skins such as banana and

6. DISCUSSION

pear are easily bruised with the continuous touch. Also, fruits such as apple, pear and banana release a natural ripening hormone called ethylene, when we handle such fruits, our touch can potentially transfer ethylene from our skin to the fruit's surface. Fruit ripening and softening are major attributes that contribute to perishability in fleshy or climacteric fruit. In these fruits (e.g., tomato banana, mango, avocado etc.), it takes about a few days after which it is considered inedible due to over-ripening (32).

6.1.1 Role of ethylene in fruits ripening

The ripening of fleshy fruits represents the unique coordination of developmental and biochemical pathways leading to changes in color, texture, aroma, and nutritional quality of mature seed-bearing plant organs. The gaseous plant hormone ethylene plays a key regulatory role in ripening of many fruits, including some representing important contributors of nutrition and fiber to the diets of humans. Examples include banana, apple, pear, most stone fruits, melons, squash, and tomato (33). The changes in the different ripening parameters such as respiratory climacteric and ethylene production will also depend on whether the fruit has been ripening naturally or artificially by exposure to ethylene or other hydrocarbons. Artificial ripening of climacteric fruits generally hastens the process of ripening. Though it leads to faster spoilage as well, it is practiced largely due to its utility towards early marketing benefit (34).

6.1.2 Preservation of the fruit freshness

Acids have been known to be used to maintain the freshness of fruits after harvesting. These acids sometimes are often used with other coating material to prevent quick decomposition of the fresh fruits. Chitosan (CTS), as an ideal coating material, has been used for post-harvest treatment of fruits and vegetables. The effects of coating with 1.5 percent CTS, alone or combined with 10 mmol L⁻¹ ascorbic acid (AsA), on post-harvest quality and core browning (CB) incidence in pears during storage at room temperature (25 ± 1 °C) were investigated in this study (35). With this, fruits can be well kept and fresh for a longer period irrespective of human touch, mechanical impact and micro-organism attack that may occur to it.

6.2 Room for improvement

There is a need to evaluate and increase the number of fruits to get the absolute results and better quality comparison of the fruits. Also, the outcomes demonstrated that our method accurately characterizes produce if the light can pass through the surface of the fruits. This usually applies to fresh produce because any degradation causes the fruit's external surface to soften. In these circumstances, low-cost multispectral imaging—that is, enhancing the sensor with LEDs that operate at many wavelengths can increase the performance of our method.

6.2.1 Adaptive calibration

Light sensors can profit from adaptive calibration systems that change sensor settings according to fruit type and environmental factors. The parameters of light absorption and reflectance may differ amongst fruits, and environmental elements like humidity. Adopting adaptive calibration algorithms can provide precise readings in a variety of situations.

6.2.2 Incorporating other sensing technology

The total fruit quality detection system can be improved by combining light sensors with other sensing technologies such as hyperspectral imaging, near-infrared spectroscopy, or acoustic sensors. Each sensing technique offers particular knowledge about the characteristics of the fruit, and their combination can provide a more thorough evaluation of quality factors.

Summary and Conclusion

In this thesis, we studied evaluation of freshness of five types of fruits using measurements of firmness by durometer and reflected RGB light sensor measurements. Traditional evaluation by people touching the fruits was also used and discussed. Fruits were tested using light-sensing method where intensities of red, green and blue light reflected from the surface of the fruits were measured. This non-destructive and cheap method appeared to be useable for detecting the quality of fruits.

Our experiments showed that in case of red light, reflectivity of fruit surface decreases while fruits are ripening. The decrease rate depends on the fruit type. In case of smaller wavelengths, variation of reflected light intensity while ripening depends on fruit and for some fruits, reflectivity of blue light increases with time.

It was shown from durometer-studies that firmness of fruit surface decreases when fruits are ripening. Combining light sensing method and durometer studies can give valuable information about freshness of the fruits. The experiments were carried out for human touched and untouched fruits. It was shown that the quality of touched fruits decreases more rapidly.

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Appendix

8.1 Licence, our poster and the questionnaire

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8. APPENDIX

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29/05/2023

8.1 Licence, our poster and the questionnaire

Our work was presented at the IT academy research summit at the institute of computer science, Delta building, University of Tartu on the 18th of May, 2023.

8. APPENDIX

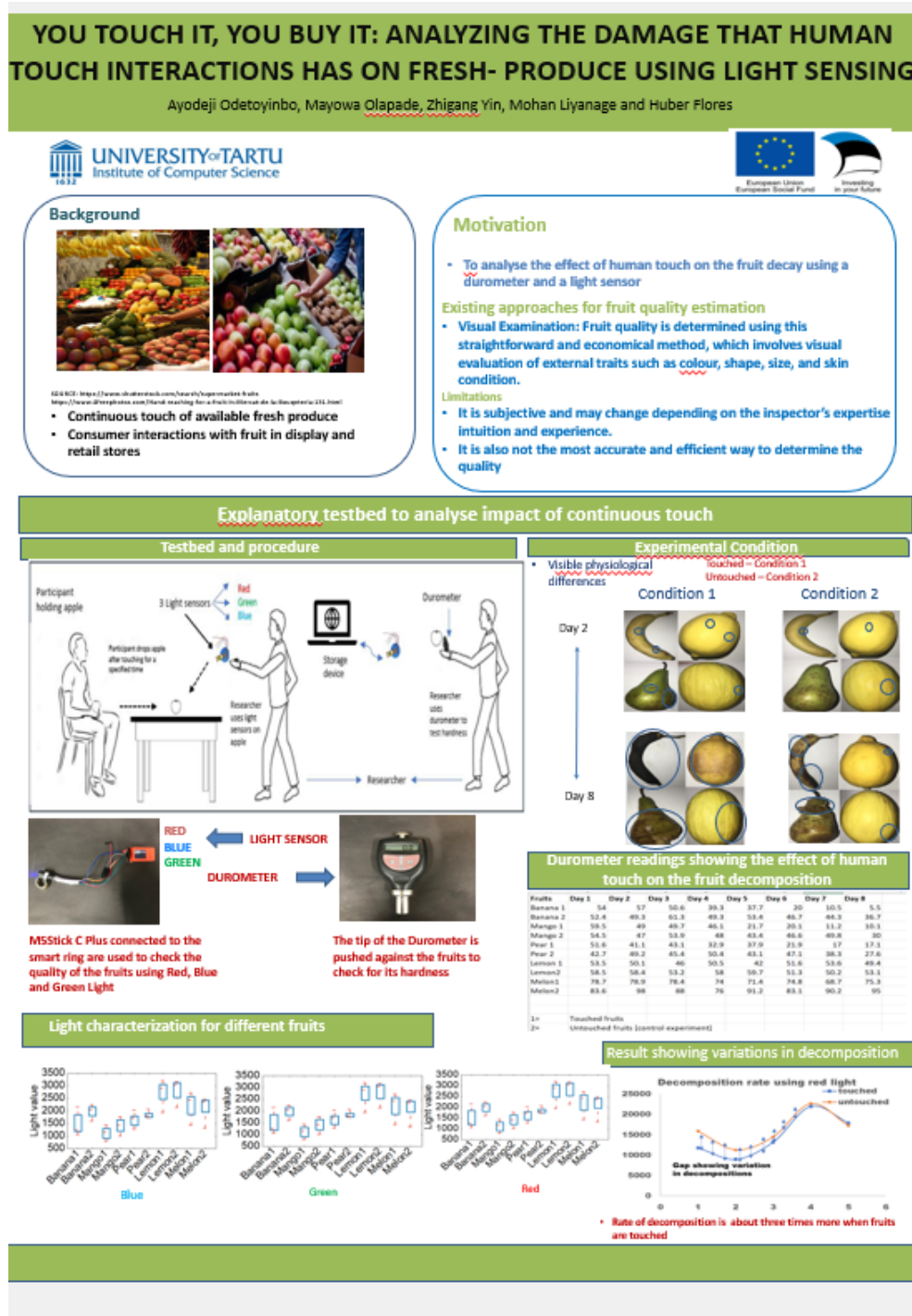


Figure 8.1: Poster presented at the academy.

8.1 Licence, our poster and the questionnaire

Fruit quality estimation

Goal: The survey aims to study the impact of manual inspection on fruit quality estimation.

Age: Gender:

Part one: for each of the questions below: choose the response that best characterises your option, where 5: Strongly Agree, 4: Agree, 3: Cannot say, 2: Disagree, 1: Strongly Disagree

Questions	Strongly Disagree	Disagree	Cannot say	Agree	Strongly Agree
"I often buy fruits"	1	2	3	4	5
Is this banana of good quality to eat?	1	2	3	4	5
Is this mango of good quality to eat?	1	2	3	4	5
Is this melon of good quality to eat?	1	2	3	4	5
Is this pear of good quality to eat?	1	2	3	4	5
Is this lemon of good quality to eat?	1	2	3	4	5

Part two: investigation of consumers' habits about choosing fruits.

1. Please select one or more answers. What quality attribute motivates you to buy fruits?

Appearance and color	
Texture	
Taste and smell	
Nutritional value	
Others	

2. What is your strategy of estimating the fruit quality?

Figure 8.2: Questionnaire filled by the participants.