NON-DESTRUCTIVE RIPENESS DETECTION OF GOLDEN TAIWAN MANGOES USING VISIBLE NEAR INFRARED SPECTROSCOPY

Nawwarah Nabilah Muhamad Khusaini[1], Kumar Velaiyudam[2], Rafidah Rosman[3]*

ABSTRACT

Visible-Near Infrared (Vis-NIR) Spectroscopy is a non-destructive technique widely used by researchers in agriculture to determine fruit quality, especially fruit ripeness. The researcher can determine fruit ripeness by analysing light reflectance and correlating it with biochemical fruit properties. The traditional method for determining fruit ripeness is destructive, subjective, and inefficient. The objective of this research is to develop a non-destructive prediction model for the ripeness of Golden Taiwan Mangoes by using Vis-NIR Spectroscopy at 780 nm. The study also evaluates the relationship between reflectance and destructive measurements over 7 days of ripening. 24 mango samples were analysed using Vis-NIR Spectroscopy and destructive methods, including soluble solids content (SSC) and firmness. The procedure included calibration of spectroscopy and data collection of spectral and reflectance measurements in a controlled dark room. Reflectance at 780 nm showed strong correlation with SSC (R^2 = 0.9625), shelf days (R^2 = 0.9626), and a moderate correlation with firmness (R^2 = 0.5905). This suggests that Vis-NIR Spectroscopy is an accurate and reliable non-destructive method for determining the ripeness of Golden Taiwan Mangoes, particularly at 780 nm. This method can enhance the efficiency of the supply chain, reduce fruit waste, and promote sustainable farming practices.

Keywords: Vis-NIR Spectroscopy, Mangifera indica (Golden Taiwan Mango), Reflectance Measurement, Fruit Ripeness Prediction, Postharvest

1. INTRODUCTION

Mangifera indica (Golden Taiwan Mango) is widely known in Malaysia. Mangoes are also widely consumed for their high fibre content and bioactive compounds, including provitamin A carotenoids, vitamin C (ascorbic acid), and phenolics [1,2]. Mangoes are generally harvested at the physiologically mature stage and ripened for optimal quality [3]. Each fruit has a different maturity time. Unripe fruit typically has a sour or bitter taste due to its underdeveloped flavour and hard texture. As the fruit

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matures, its nutrient levels increase. The fruit is particularly suitable for eating at this stage due to its sweetness and juiciness. Conversely, overripe fruit exhibits a soft texture and gradually develops bruises.

If the fruit is harvested at an early stage, it will not ripen properly, but if it is harvested while still unripe or immature, it will spoil faster and cannot be exported [4]. The maturity of fruit is significant at harvest because it affects its storage life and quality. Immature fruits are more prone to shrivelling and mechanical damage and have inferior flavour when ripe. Overripe fruits are likely to become soft and have a bland taste soon after harvest. Fruits harvested either too early or too late in their season are more susceptible to postharvest physiological disorders compared to those picked at the proper maturity [5]. Assessing fruit ripeness is crucial in the agricultural industry, as it greatly impacts quality and market value [6]. Traditionally, methods used to determine the ripeness of fruit involved destructive techniques such as examining colour, smelling for aromatics, feeling for softness, and disintegrating the produce, which leads to product loss and waste. These methods are prone to error, lack consistency across evaluations, and are exceedingly time-consuming. This method was less efficient for rapid testing on the grading line due to its subjectivity [7, 8, 9]. Food waste is contrary to Sustainable Development Goal (SDG) 12, which aims to reduce food waste by 50% at the retail and consumption stages and food loss at the production stage, including post-harvest losses, by 2030 [10]. Hence, there is growing interest in developing a non-destructive method, such as Visible Near Infrared Spectroscopy (NIRS), to determine fruit ripeness. From there, it is possible to establish a prediction model based on the relationship between spectral characteristics and destructive measurements (soluble solid content (SSC) and firmness) of the fruits. The fruit sample used in this research is Mangifera indica (Golden Taiwan Mango).

There are several methods to determine fruit ripeness. Assessments of fruit quality rely on traditional destructive processes, including measurements of firmness and Soluble Solid Content (SSC). Firmness is one of the essential maturity indicators used to classify fruit according to maturity level, as the firmness of fruit flesh decreases during the ripening process [11]. A handheld or automated penetrometer commonly determines this by squeezing or pressing the outer layer of fruits [11]. Other maturity indicators, such as size, colour, and sweetness, also need to be considered to confirm the maturity of these fruits, since starch begins to break down into sugars as the fruit ripens [11]. The term "brix meter" is used to refer to total soluble solids (TSS) and SSC [11]. Although destructive approaches are accurate, they have several drawbacks, including the need for laborious sample preparation, handling damaged samples, and difficulty tracking changes within the same fruit over time. Recognising these constraints makes various techniques more dependable and faster, and non-destructive methods can achieve these goals.

Visible Near-Infrared (Vis-NIR) Spectroscopy is also a non-destructive method for determining and predicting fruit ripeness. UV/VIS/NIR spectroscopy is a powerful analytical technique for assessing the optical properties of liquids and solids (transmittance, reflectance, and absorbance) [12]. NIR spectroscopy is a non-destructive analytical technique that involves the interaction of near-infrared radiation with a sample. The NIR region of the electromagnetic spectrum is situated between the visible and mid infrared regions, typically ranging from 780 to 2500 nanometres. NIR spectroscopy identifies and quantifies various chemical components in a sample, such as moisture, protein, fat, and sugar content in food and agricultural products [13].

The paper [14] states that visible near-infrared (NIR) spectroscopy is a non-invasive method for determining mango quality because it can successfully differentiate between healthy and affected mangoes using principal component analysis for feature extraction and selecting the optimal wavelength range (650-970 nm). Machine learning models such as linear discriminant analysis, support vector machines, and logistic regression can achieve up to 99% accuracy. This can help detect the internal disorder and reduce postharvest losses. Additionally, the study in [15] used NIR Spectroscopy for online and offline scanning of Mangifera indica CV. ‘Nam dok mai-si Thong’ mango. The objective of this paper was to measure the overall accuracy of the Brix value as the reference. The result shows that offline scanning achieved higher accuracy than online scanning, with scanning repeatability of 0.00199 for offline and 0.00993 for online. The reproducibility values for offline and online are 0.00279 and 0.00513, respectively. The reference measurement repeatability was 0.2, and the maximum $R^2 = 0.894$. In summary, this research examines how Vis-NIR spectroscopy at 780 nm can relate fruit properties to their quality. This research aims to develop a predictive model to determine the ripeness of Mangifera indica (Golden Taiwan Mango). This study will help evaluate fruit ripeness by providing an accurate and reliable method. Fully mature, nutrient-rich mangoes can increase market demand and improve consumer health. Accurate ripeness classification can reduce food waste and increase the consumption of high-quality fruits.

2. METHODOLOGY

This study incorporates non-destructive (Vis-NIR reflectance spectroscopy) and destructive analyses (SSC and firmness) by measuring reflectance spectra. This experiment was conducted to assess mango properties at different stages of ripening and shelf life. Experiments were carried out for 7 days of shelf life for Mangifera indica (Golden Taiwan Mango).

2.1 Sample Preparations

The mangoes were harvested from the fruit orchard and collected in Sekinchan. All twenty-four mangoes were hard, indicating they were not yet ripe. Most of the mangoes displayed green skin, though several had small red spots. Neither of the mangoes was treated with any chemical solutions nor ripening agents. The mangoes matured naturally without intervention. The samples would then be cleaned and numbered, and visual inspections of size and colour would be carried out in the laboratory. This step was crucial to minimize external factors that could affect the analysis of the fruit samples' spectra. The samples would then be stored at room temperature (24-28 °C) before experimentation. A paper towel would be used to remove any residual dirt and moisture from the samples' surfaces before taking measurements. **Figure 1** shows the progression of the mango from day 1 until day 7.

Figure 1. The progression of the mango from day 1 to day 7

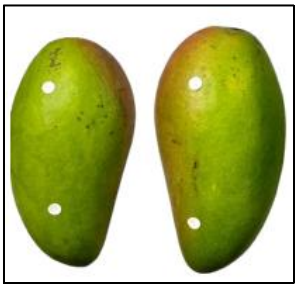

Figure 2. The marked location for reflectance scanning on the mango on both sides

The reflectance spectra data were obtained by scanning the outer skin of the mango samples. Each sample was scanned four times at marked points around the fruit as shown in **Figure *2***. The four scans for each mango were subsequently averaged for enhanced accuracy. Three mangoes were scanned daily from day 1 through day 7, capturing spectral changes throughout the ripening process, from unripe to overripe. The reflectance spectra obtained were stored in Microsoft Excel. Origin software was also used to smooth the noise further in the reflectance spectra.

2.2 Non-destructive Analysis

The experiment was conducted using specialized equipment, including a Visible-Near Infrared Spectrometer (Avantes, AvaSpec-2046L), a reflectance probe (200-1100 nm, R400-7-SR, Ocean Insight), and a tungsten halogen light source (360-2000 nm, Ls-1, Ocean Optics). It will examine the light that is reflected from the fruit's surface to evaluate the reflectance spectra properties. The halogen light source will be emitted through the reflection probe, and the sensor inside the reflection probe will detect the reflected light and collect the reflected data in the spectrometer. This method can determine the fruit quality without damaging the fruit. To ensure the accuracy of the measurement, the experiment was conducted inside a lightproof box to prevent interference from external light. The interior of the box was also lined with black cloth to prevent interference from the inner surface.

The distance between the sample surface and the reflectance probe is an important parameter that must be measured accurately. The distance between the reflectance probe and the sample was maintained at 6 mm. The increasing distance would release a more intense light source from the probe to the skin surface. This will potentially give an inaccurate reading. Conversely, shorter distances between the probe and the sample would restrict the area of reflectance reading on the skin sample [16]. The trigonometric function was used to ascertain the diameter of the reflectance taken from the fruit surface. The probe was positioned at a 90° angle using a retort stand. This positioning relative to the sample could potentially create a right triangle, as depicted in **Figure 3**. The trigonometric function was employed to compute the diameter of reflection of the fruit's surface. As shown in **Eq. (1)**, this function was used to determine the reflectance diameter from the fruit's surface. According to its specification, the angle of light emitted from the probe is θ = 12.5°. On the other hand, the distance between the probe and the sample is 0.6 cm. With these parameters, the opposite side, x, is calculated, representing the radius of the circle. Lastly, the diameter of the emitted light is derived from the computed radius, yielding 0.266 cm.

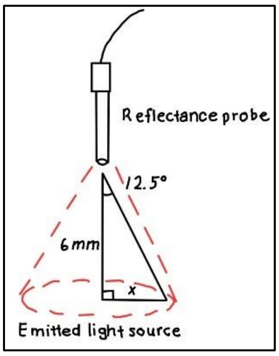

Figure 3. Diameter of collected reflectance data

$$tan\ \theta = \frac{opposite}{adjacent} \tag{1}$$

The spectrometer is turned on for 10 minutes once the experiment is set to allow it to warm up. This step ensures that the light source and detectors are stabilized before calibration. Then, calibrations were conducted with a white reference, and a dark reference was recorded in AvaSoft Software. Perform a white reference by placing a white reference standard at a Tungsten Halogen Light to establish a 100% reflectance baseline. Next, the dark reference is performed by placing the dark reference standard in front of the Tungsten Halogen Light to establish the 0% reflectance baseline. During the calibration process, the integration time for this reflectance measurement is 134 ms, and five-wavelength averaging is employed to obtain a smoother output. The spectral information is measured at five consecutive wavelengths. Averaging several wavelengths makes the output more stable. However, additional averaging can increase the spectrometer's measurement time. Therefore, five-wavelength averaging was used to achieve a suitable and reliable setting.

Next, the reflectance spectra data will be obtained by measuring the outer skin samples. Each sample was scanned four times at four marked locations around the mango. Thus, four scans were obtained for each fruit and averaged. Three mangoes were measured daily from day 1 to day 7, covering the spectrum from unripe to overripe shelf days. **Figure 4** and **Figure 5** illustrate the schematic of the reflectance measurement setup and the configuration inside the box for reflectance methods, respectively. The reflectance spectra obtained were stored in Microsoft Excel. Origin software was also used to smooth the noise further in the reflectance spectra.

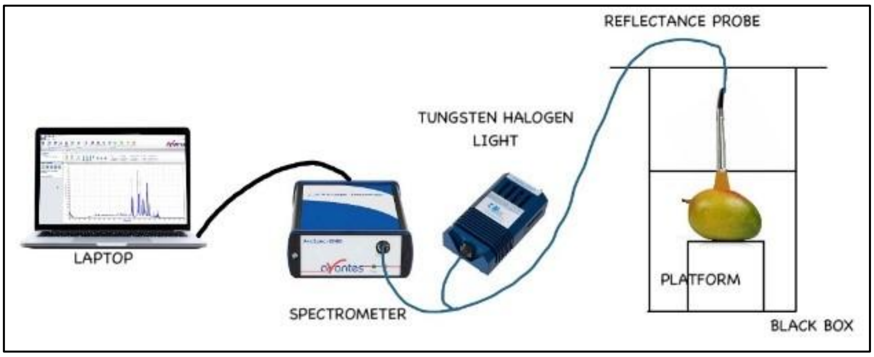

Figure 4. Schematics of the reflectance measurement setup

Figure 5. Set up inside the box of the reflectance measurement

2.3 Destructive Analysis

Destructive methods were also used to accurately measure critical parameters such as firmness and soluble solids content (SSC). This was carried out to ensure that the actual values of these parameters were reached and used for non-destructive method analysis. Four replicate measurements were taken for each sample to ensure high data reliability. The four readings per sample were averaged.

2.3.1 Soluble Solid Content Measurement

The soluble solids content (SSC) of the mango samples was determined using a digital refractometer (ATAGO PAL-1), with results expressed in degrees Brix (°Brix). Before taking sample measurements, the refractometer was calibrated to ensure accurate data. Calibration involved placing a few drops of distilled water on the refractometer's measuring surface, ensuring the prism was fully covered. Press the “Zero” button until the screen reads and shows 0.0. This process needs to be performed at room temperature to ensure the refractometer provides consistently accurate measurements. After that, the SSC measurement can be conducted. Mango juice had been extracted, and a few drops were fully placed on the prism of the refractometer without air bubbles as shown in ***Figure 6***. The °Brix will be displayed after the start button press. To avoid cross-contamination between samples, the refractometer's prism was cleaned after each sample. The process was repeated for 3 samples each.

Figure 6. Measurement of Soluble Solid Content using a digital refractometer

2.3.2 Firmness Measurement

The 11 mm head diameter GY-03 Sclerometer Farm Hardness, with a range of 1 to 24kg/cm, was used to measure the firmness of the Golden Taiwan Mango. The calibration was performed before the measurement to ensure accuracy and eliminate potential differences in readings. The instrument needs to be clean and uncontaminated. To calibrate, adjust the knob by turning clockwise to tighten and counterclockwise to loosen. Adjust the firmness meter until it points to zero when no pressure is applied to the instrument. To measure the firmness of the mango, the skin was cut to expose the mango's flesh. Force was applied to the meter on the mango's flesh as shown in **Figure** *7*, and the meter measured the resistance level. To ensure accuracy and reliability, four readings were taken for each sample with the same force.

Figure 7. Firmness measurement using a GY-03 sclerometer for farm hardness

3. RESULT

The data on mangos were collected from day 1 to day 7 of shelf life, covering the unripe to overripe phase. Microsoft Excel will be used to analyse the collected data. Then, a comparison between the reflectance spectral data and destructive data will be conducted using a graph, with reflectance (%) as the dependent variable and destructive parameters (SSC and firmness) as the independent variables. From the graph, an analysis can be conducted to determine and predict mango ripeness parameters. The result comprises the number of shelf days, reflectance measurements at 780 nm, °Brix, firmness, and a table of modelling equations.

3.1 Non-destructive Analysis

The reflectance spectral curves of mango samples during the ripening process are presented in **Figure 8**. According to [18], changes occur in mango reflectance spectra as the fruit transitions from unripe to overripe phases. It was observed that the spectra exhibited a similar overall curve pattern from day 1 to day 7, but with different reflectance intensities in specific wavelength regions. However, **Figure 8** does not show a clear direct relationship between the full spectral curve and the number of storage days.

It is important to understand the physiological changes that occur during ripening and how they influence light reflectance across different wavelengths. 400 – 700 nm is the visible region where the spectral curve is usually determined by pigment optical properties such as chlorophyll, anthocyanins, and carotenoids. This is because, during the ripening process, chlorophyll degradation reduces the green pigment, while carotenoid accumulation increases the development of orange and yellow colour on the mango skin. During the seven days of the ripening process, the shape of the spectral curves remains the same, but the value of reflectance is different. This may be due to changes in pigment composition, surface colour, and fruit physiology during ripening [17]. However, pigment degradation and accumulation do not occur at the same rate in every fruit; therefore, spectral curves may overlap. This usually happens when mangoes are at intermediate stages of ripening. The near-infrared region is from 760 to 860 nm. The spectral characteristics in this region are usually determined by changes in internal factors of the fruit, such as organic acids, soluble solids, water status, and tissue structure [18, 19]. Organic acid concentration will decrease while sugar content increases during the ripening process. This is due to starch breakdown and other biochemical processes. The internal changes will affect the light absorption and scattering within the mango tissue. At 780 nm, the reflectance is determined by a combination of pigment changes, tissue softening, and moisture distribution. Besides that, it is also controlled by light scattering from the mango surface and internal cell structure. Therefore, the selected wavelength of 780 nm was further extracted and analysed, as shown in **Figure 9**.

In summary, reflectance analysis can detect the pigment changes. Besides that, it can also support the non-destructive monitoring of biochemical and physical changes during the ripening process. Next, visible wavelengths can provide information about skin colour and pigmentation, while near-infrared wavelengths can indicate changes in internal quality. Therefore, **Figure 8** can provide the spectral basis for selecting 780 nm as a representative wavelength for further analysis.

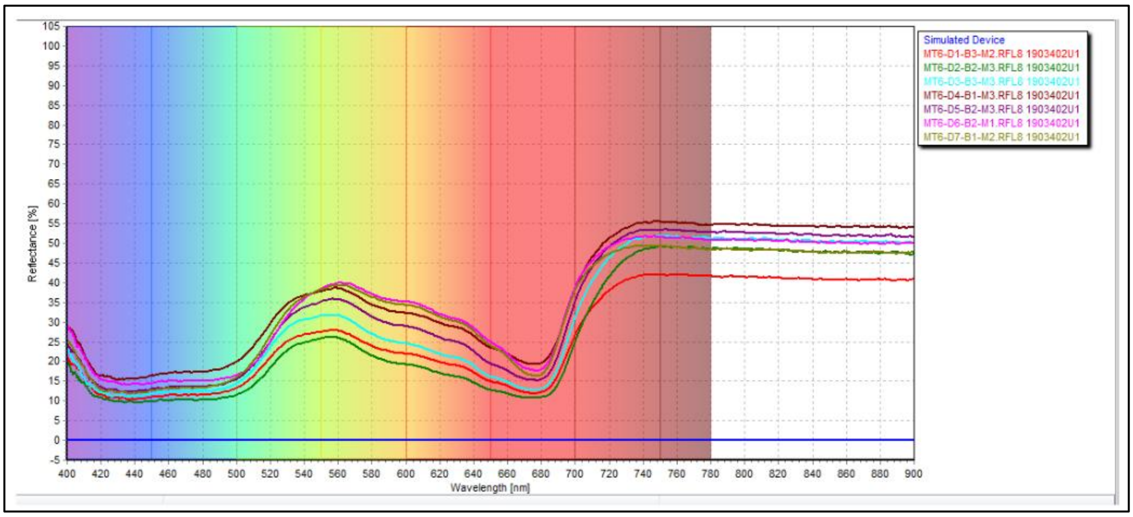

Figure 8. The pattern of reflectance of mango from day 1 until day 7

Figure 9 shows the relationship between reflectance (%) at 780 nm and mango storage days over seven days of ripening. This figure shows a clearer relationship between reflectance and days. From this figure, reflectance increases from day 1 to its maximum on day 4. After day 4, the reflectance value started to decrease. The graph indicates the mango started to overripe after day 4. The regression result showed $R^2 = 0.9626$. This shows strong potential for reflectance at 780 nm in monitoring mango ripeness. The changes in physical and biochemical properties during ripening account for the increase in reflectance from day 1 to day 4. During this process, chlorophyll degradation reduces light absorption, and carotenoid accumulation develops the yellow and orange colour [17]. These changes make the surface of the fruit brighter and more reflective. Besides, changes in soluble solids and organic acids may influence NIR reflectance in the 760-860 nm range [18,19].

Figure 9 shows that the reflectance value began to decrease after day 4. This decrease is due to structural changes in mango tissue resulting from moisture loss and enzymatic activity. Besides that, the degradation of the cell wall had caused tissue softening. Additionally, the changes in scattered light inside the mango also occurred due to transpiration and respiration, where water was lost. During the overripe phase, reflectance was lower because the pigment on the fruit's skin had experienced oxidation and surface darkening [20,21]. Therefore, the reduction in reflectance after day 4 suggests that the optical response at 780 nm is sensitive. This aligns with Figure 9, in which reflectance begins to decline after reaching its peak [21]. Overall, **Figure 9** clearly shows that the reflectance at 780 nm is more strongly related to storage days. The reflectance increased from day 1 to day 4 due to changes in ripening pigments and biochemical development. Then, started to decrease after day 4 due to moisture loss, tissue softening, and structural changes. This confirms that the relationship between spectral and storage days is not obtained from the full spectrum alone. It becomes clearer when the selected wavelength of 780 nm is analyzed separately. Therefore, 780 nm was considered a suitable wavelength for representing mango ripening behaviour in this study.

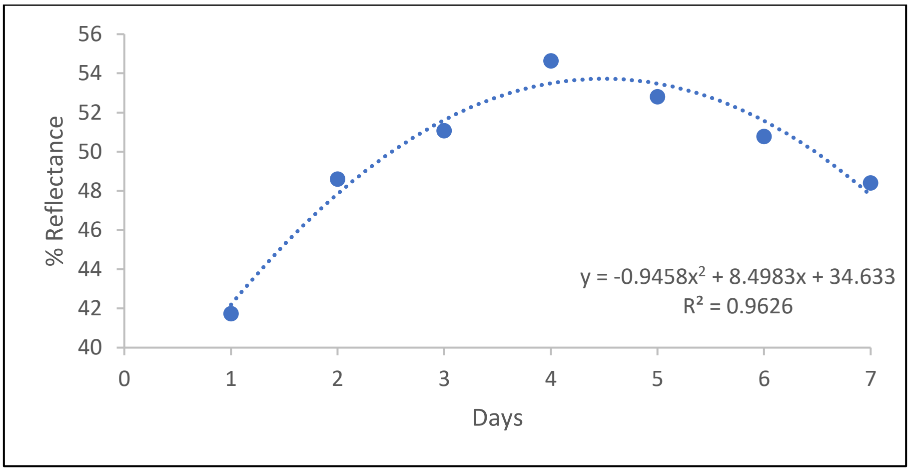

Figure 9. Relationship between reflectance at 780 nm and mango storage days over 7 days of ripening

To further support the selection of 780 nm, an additional absorption and scattering analysis was combined. Since the Vis–NIR system measured reflectance rather than direct optical absorption and scattering coefficients, the absorption/scattering response at 780 nm was estimated using an apparent optical index instead of being reported as a true absorption or scattering coefficient. The Kubelka–Munk transformation as in **Eq. (2)** can be used to convert reflectance into an apparent absorption to scattering indicator, where R is the reflectance expressed as a decimal [22]. This additional graph helps explain how changes in reflectance at 780 nm may be linked to absorption and scattering behaviour during mango ripening, as shown in **Figure 10**. Since the reflectance increased from day 1 to day 4, the value of F(R) decreased from 0.40689 to 0.18845. After day 4, the value began to increase again, reaching 0.27507 on Day 7. This shows that the Kubelka–Munk graph has the opposite behaviour to reflectance. This is normal because F(R) is the mathematical inverse of reflectance.

$$F(R) = \frac{(1-R)^2}{2R} \qquad (2)$$

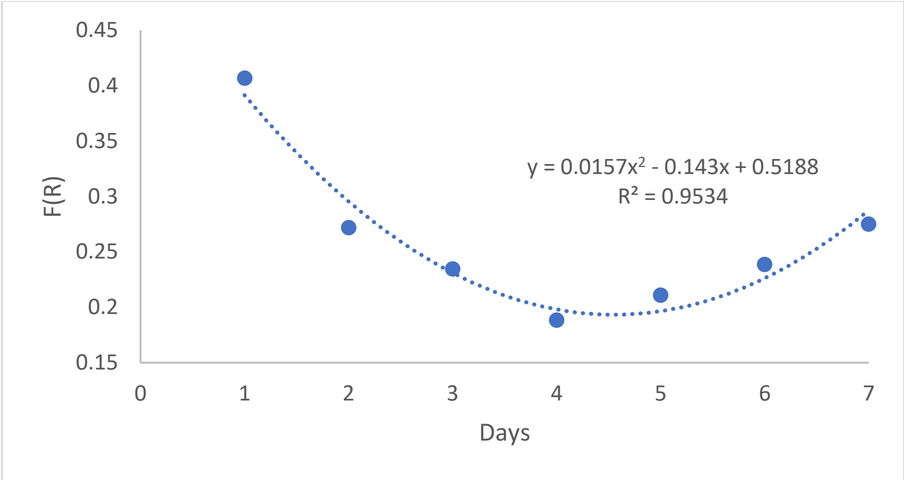

Figure 10. Apparent absorption to scattering at 780 nm during the 7 days ripening process

3.2 Destructive Analysis

In destructive analysis, firmness and Soluble Solid Content (SSC) were measured. Both parameters, firmness and SSC, are measured by the number of shelf days from day 1 to day 7, reflecting the progression from unripe to overripe. This section will discuss the relationships among firmness, soluble solids content, shelf life, and reflectance.

3.2.1 SSC Measurement

Figure 11 shows the relationship between soluble solid content (SSC) and shelf days from day 1 until day 7. The SSC value increases from 6.18 °Brix on day 1 until it reaches the peak at 13.18 °Brix on day 4 before decreasing to 10 °Brix by day 7. The polynomial regression equation that best fits the data is $Y = -0.4911x^2 + 4.6196x + 2.2714$, with a very high coefficient of determination ($R^2 = 0.9797$), indicating that the change in SSC correlates well with storage time.

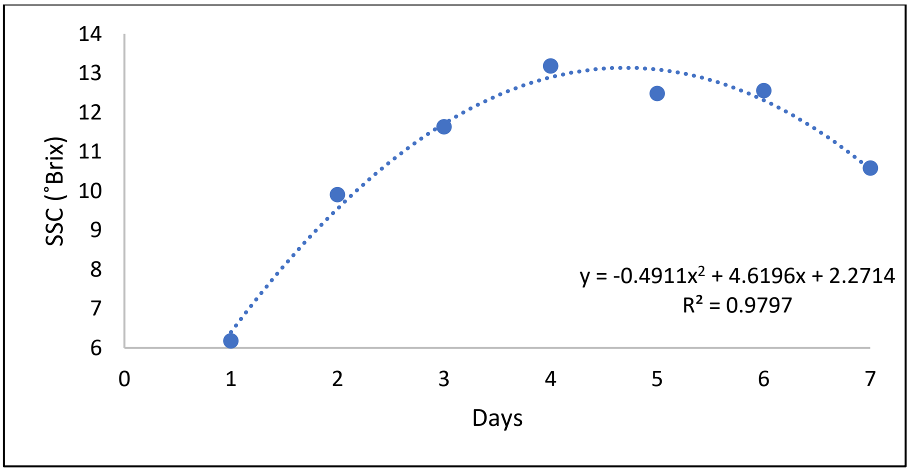

Figure 11. Relationship between soluble solid content and mango storage days over 7 days of ripening

At the early stages, the starches and complex carbohydrates are converted into simpler sugars such as glucose, fructose, and sucrose. This process enhances the fruit's sweetness, thereby increasing the °Brix value [12]. The additional mango ripening process enhances respiration. As a result, the sugar is converted into energy, carbon dioxide, and water. Subsequently, the SSC level started to decrease. Over ripening can also occur during extended storage, as sugars are diverted to secondary metabolic processes due to high moisture and cell breakdown [13]. Besides, ethylene production plays an important role in regulating the conversion of starch to sugar and enhancing enzymatic activity. As ethylene production increases in subsequent stages, senescence also increases. Hence, the sugar content was reduced due to over respiration [23]. In conclusion, the graph shows changes in SSC during mango ripening, the line initially increases, then declines. The increases in SSC are due to starch hydrolysis, while the decrease is due to sugar metabolism and respiration. The biochemical changes must be interpreted to optimize post-harvest storage conditions and maintain fruit quality.

Figure 12 shows a quadratic relationship between SSC and reflectance with $R^2 = 0.9625$, indicating a strong correlation. As reflectance increases, SSC rises, indicating that fruits with higher surface reflectance generally have higher sugar content related to ripeness. As the mango fruit ripens, starch converts into sugars such as glucose, fructose, and sucrose, resulting in an increase in the sugar content of the mango. Besides, the reason the colour of the mango changes is that the green stuff in the mango, called chlorophyll, breaks down, and the yellow and orange colours, such as β-carotene, become visible, which is what gives the mango its yellow and orange colour [24]. Since chlorophyll reflects light, when it breaks down, the mango starts to reflect light. In summary, these biochemical and optical transformations provide a strong basis for the observed correlation between reflectance and SSC. The R^2 value supports the reliability of using reflectance as a non-destructive surrogate for SSC estimation. Consequently, reflectance measurement presents a practical and effective method for assessing mango ripeness through rapid, non-invasive analysis.

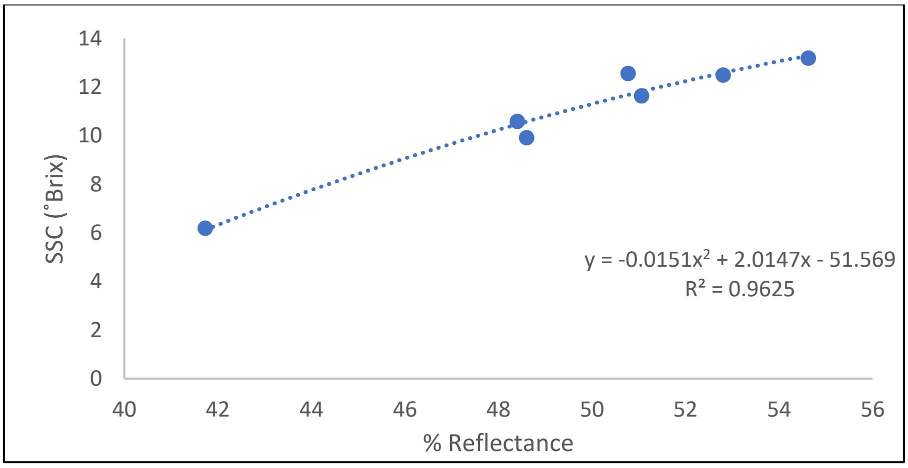

Figure 12. Relationship between soluble solid content and reflectance at 780nm

3.2.2 Firmness Measurement

Figure 13 shows the relationship between firmness and the storage day from day 1 to day 7. The graph shows a decrease in firmness as mangoes ripen and soften. On day 1, firmness values were around 9.3 kg/cm² and decreased to around 0.55 kg/cm² by day 7. The polynomial regression equation for the data is $Y = 0.2969x^2 - 3.866x + 13.089$, with $R^2 = 0.9861$. The high correlation shows that firmness loss follows a predictable mathematical trend during ripening. The main loss of firmness in the fruit during ripening was due to physiological and biochemical changes. The enzymes are one of the factors that cause the change. The main reason for the reduction in firmness is enzymatic degradation. Fruit tissues become less resistant because the pectinase and polygalacturonase enzymes break down the pectin in the cell walls. To speed up the softening process, cellulase accelerates the decomposition of cell wall cellulose [21].

The ripening process of the mango also leads to water loss through transpiration. The decrease in water volume will affect the pressure in fruit cells [9]. According to the previous study [25], tissue softening occurs because starch is converted into sugars, such as glucose, sucrose, and fructose, during ripening. The conversion of complex carbohydrates into soluble content also makes the mangoes softer and creates a softer texture.

The other factor that influences the ripening process is the development of ethylene. To start the ripening process, the plant will use the hormone ethylene to activate the biochemical pathway. The wall breakdown process will be faster. Ethylene production increases until the mangoes reach peak maturity. This process causes a loss of firmness in the mango. The temperature and humidity can also affect the rate of firmness loss. To conclude, as storage temperature increases, both enzyme activity and ethylene production rates increase. All these processes had increased the ripening process. Subsequently, as the temperature decreases, the ripening rate process also decreases [23]. In conclusion, the results indicate a relationship between days and firmness, with an R^2 of 0.9861. Enzyme, moisture loss, starch to sugar conversion, and ethylene were the factors that affect the softening of the fruit.

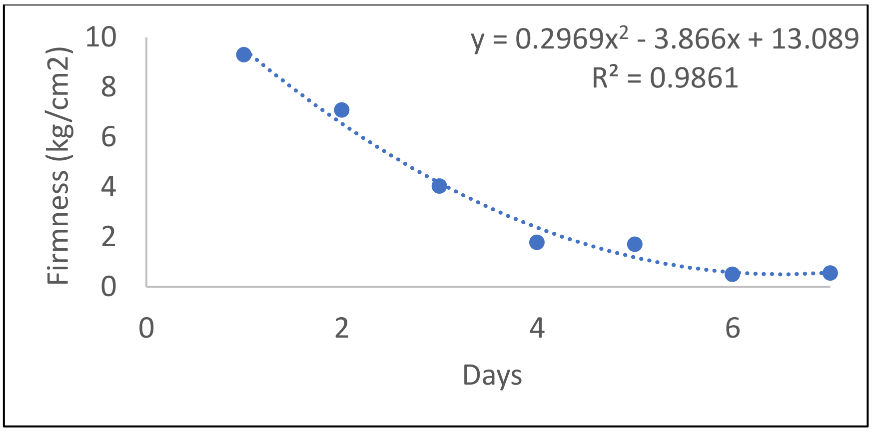

Figure 13. Relationship between firmness and mango storage days over 7 days of ripening

Figure 14 shows the relationship between the firmness and reflectance at 780 nm with a moderate $R^2 = 0.5905$. This shows that the reflectance value has increased while the firmness has decreased. This indicates that the softer the mango gets, the higher the reflectance value. This relationship demonstrates the natural ripening process, in which the fruit's surface becomes less firm as the internal structure breaks down. During fruit ripening, softening occurs due to enzymatic breakdown by enzymes such as polygalacturonase and pectin methyl esterase. This will weaken the cell walls by degrading pectin, hemicellulose, and cellulose [21]. The firmness has decreased because turgor pressure within the fruit cell has decreased due to water loss. Water loss was occurring due to respiration and transpiration. The process of carotenoid accumulation and chlorophyll degradation at higher values increases reflectance. The R^2 value indicates that a decrease in firmness requires factors beyond a single measurement parameter, as external environmental conditions, such as temperature, humidity, and handling practices, produce excessive variations in firmness that reflectance alone cannot explain [26].

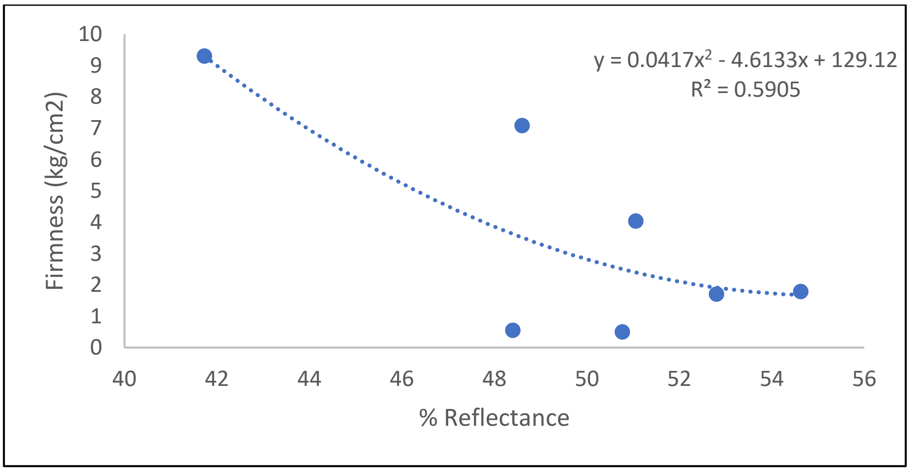

Figure 14. Relationship between firmness and reflectance at 780nm

Figure 12 and **Figure 14** show that the reflectance can identify the mango ripeness. Soluble solid content has a positive relationship, while firmness has a negative relationship. It can be concluded that as reflectance increases, sweetness increases while firmness decreases. Reflectance measurements show high accuracy in determining fruit sweetness, with $R^2 = 0.9625$. This shows the great potential for identifying the preferred consumer qualities. The firmness analysis shows a moderate correlation($R^2 = 0.5905$). Reflectance can still help track the mango's softening, but to obtain an accurate firmness assessment, another analytical tool is required.

3.3 Modelling Equation

Polynomial regression models were developed to describe the relationships among mango shelf days, reflectance response, and destructive parameters such as soluble solid content and firmness. **Table 1** presents the shelf day models, where (x) represents the number of shelf days. Meanwhile, **Table 2** presents the reflectance models, where (x) represents the percentage reflectance measured at 780 nm.

Table 1. Modelling equations for reflectance, SSC, and firmness

Predicted Parameter	R^2	Modelling Equation	Independent Variable
Reflectance at 780 nm (%)	0.9626	$Ref@78 = -0.9458X^2 + 8.4983X + 34.633$	X = shelf day
SSC (°Brix)	0.9797	$SSC = -0.4911X^2 + 4.6196X + 2.2714$	X = shelf day
Firmness (kg/cm²)	0.9861	$Firmness = 0.2969X^2 - 3.866X + 13.089$	X = shelf day

Table 1 presents the polynomial regression equations for reflectance, SSC, and firmness as functions of shelf days. In this table, X represents the number of days. The reflectance model produced $R^2 = 0.9626$. This proves that the reflectance at 780 nm was related to shelf days. Next, the SSC model gave $R^2 = 0.9797$, suggesting that SSC was strongly related to the day. Lastly, firmness also shows a strong relationship with days, with $R^2 = 0.9861$.

Table 1 is useful because it shows the ripening behaviour of mangoes over seven days. Reflectance increased from the early ripening stage, peaking before decreasing at the next stage, while SSC increased as starch was converted into sugars. In contrast, firmness decreased as the mango tissue softened during ripening. Therefore, **Table 1** is mainly used to describe how the measured parameters changed with storage duration.

Table 2. Reflectance modelling equations for SSC and firmness at 780 nm

Predicted parameter	R^2	Modelling equation	Independent variable
SSC (°Brix)	0.9625	$SSC = -0.0151X^2 + 2.0147X - 51.569$	X = reflectance at 780.028 nm (%)
Firmness (kg/cm²)	0.5905	$Firmness = 0.0417X^2 - 4.6133X + 129.12$	X = reflectance at 780.028 nm (%)

Table 2 shows the reflectance models, where x represents the percentage reflectance at 780 nm. This table focuses on the use of Vis-NIR reflectance as a non-destructive indicator for estimating mango quality parameters. The SSC model achieved a high R^2 value of 0.9625, indicating that reflectance at 780 nm was strongly related to soluble solid content. This suggests that reflectance measurements can serve as a reliable, non-destructive indicator for estimating mango sweetness. On the other hand, the firmness shows $R^2 = 0.5905$. This shows that there is only a moderate relationship between reflectance and firmness. This implies that while reflectance may indicate fruit softening, firmness may also be influenced by additional factors, including tissue structure, moisture loss, and surface variation. For firmness analysis, further investigation is required.

In conclusion, the modelling equations provide a better interpretation of the results. **Table 1** explains how reflectance, SSC, and firmness change during storage. **Table 2** highlights the potential of reflectance measurement as a non-destructive method for estimating mango ripeness.

4. CONCLUSION

Studies using Visible Near-Infrared Spectroscopy at 780 nm successfully determined the ripeness of Mangifera indica (Golden Taiwan mango). This experiment successfully determined the ripeness of mangoes from unripe to overripe. The reflectance spectra across different shelf life stages show significant correlations with soluble solids content (SSC) and firmness. The predictive models achieved high R^2 values of 0.9625 for SSC, 0.5905 for firmness, and 0.9626 for shelf days. This indicates a strong relationship between reflectance at 780 nm and biochemical changes during mango ripening. Besides that, it also proves that Vis-NIR spectroscopy can be a reliable, non-destructive, and rapid method. This method can accurately determine the maturity of the mangoes. The success of this experiment can improve the quality control of post-harvest. Additionally, this method also helps reduce fruit loss. Lastly, this method can also improve the standardization of fruit grading.

Future developments should highlight the incorporation of this method into real-time automated grading systems. Besides, developing portable Vis-NIR devices at low cost could increase the use of this method into field applications. Next, by integrating artificial intelligence (AI) into this method, it can increase the accuracy of the results. In conclusion, integrating Vis-NIR spectroscopy with automated grading, AI prediction models, and portable instruments can significantly transform the fruit industry.

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