Kinetics of quality changes in papayas (Carica papaya L.) coated with Malaysian stingless bee honey

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ABSTRACT

There have been increased efforts to identify new edible coating and preservative compounds derived from natural sources. This study aimed to investigate the effect of two different concentrations (1.0 % and 1.5 %) of Malaysian stingless bee honey (SBH) as an edible coating agent on the quality attributes of papayas (Carica papaya L.) during storage. Quality parameters such as fresh weight loss (FWL), firmness, soluble solids content (SSC), titratable acidity (TA), colour, and respiration rate were investigated during 12 d of storage at 12 ± 1 °C. The results indicated that papayas coated with 1.0 % and 1.5 % of SBH significantly retained their firmness, colour, SSC, and TA, in addition to the reduced FWL and respiration rate as well as delayed decay development in fruits compared to the uncoated samples. The results of the Field Emission Electron Microscopy revealed that the SBH coating also prevented the ultrastructural features of the mitochondria. In addition, the zero-order and first-order kinetic models fitted well with the experimental data for both coated and uncoated papayas using the Arrhenius law approach. These results suggest that the SBH-coated layer not only improved the postharvest quality of papayas during storage but also prolonged their storage life.

1. Introduction

Papaya (Carica papaya L.) is a climacteric fruit that is highly in demand due to its high amount of antioxidants and rich nutrient content. Nevertheless, postharvest losses due to short shelf life, disease infection, as well as high costs for shipment procedures and fungicide treatments that could be harmful to consumers remain a major threat in the production chain of papayas (Rahman et al., 2008). According to Narsaiah et al. (2015), the shelf life of papaya tends to be limited because of its climactic ripening pattern. As a climactic fruit, papaya releases high doses of ethylene to stimulate the ripening process when it is not properly stored due to its high respiration rate. In addition, disease infections such as anthracnose may significantly deteriorate the quality of fresh papayas (Maringgal et al., 2019; Sanders and Korsten, 2003). The application of fungicide may be effective in preventing infections although it poses a risk to the human health and environment (Palou et al., 2015). Besides, the frequent utilisation of synthetic fungicides may result in the creation of fungicide-resistant strains that are derived from the pathogen (Maqbool et al., 2011).

Edible coating is one of the atmosphere-modifying methods used in the fresh produce production chain that notably improves the shelf life and quality of the product. It is defined as a thin layer coating on the fruit surface that creates a barrier between the fruit and the environment (Baldwin and Hagenmaier, 2011). The edible coating is usually applied by dipping or spraying the coating solution on the fruit surface to prevent the ultrastructural features of the mitochondria. In addition, the zero-order and first-order kinetic models fitted well with the experimental data for both coated and uncoated papayas using the Arrhenius law approach. These results suggest that the SBH-coated layer not only improved the postharvest quality of papayas during storage but also prolonged their storage life.
made from natural resources such as aloe vera and cassava starch prolonged the shelf life of fruits by maintaining their quality throughout storage.

Stingless bee honey (SBH) has natural antimicrobial and contains high amounts of antioxidants and secondary metabolite compounds (Avila et al., 2019). It is naturally acidic with pH values ranging from 3.15 to 6.64 (Nordin et al., 2018). Several studies have shown that SBH possessed antimicrobial (Boorn et al., 2010; Nishio et al., 2016), antibacterial (Chan-Rodríguez et al., 2012; Temaru et al., 2007), and antifungal properties (Shehu et al., 2016; Maringgal et al., 2019). Hence, SBH has been widely used traditionally to treat various diseases in humans such as intestinal diseases and skin lesions (Rao et al., 2016). Recently, Maringgal et al. (2019) reported that SBH displayed a significant protective effect against fungus growth and Colletotrichum brevipes spore germination in papayas. This finding indicated that SBH has great potential for fruit coating due to its natural biocontrol properties. Nevertheless, based on the literature review, studies performed on SBH as an edible coating for fruits are rather limited. Besides, the published data on the modelling of quality changes in coated papayas during storage is limited as well. Therefore, this study aimed to: 1) investigate the effect of different concentrations of SBH coating on the quality of papayas during storage and 2) develop kinetic models that describe the quality changes in uncoated and coated papaya fruits.

2. Materials and methods

2.1. Preparation of papaya and SBH samples

A total of 75 fresh papayas (Carica papaya L. cv. Sekaki) with colour index two (green with trace of yellow) were used in this study. The fruit were purchased from a commercial fruits wholesaler in Selangor, Malaysia. The selected papayas were uniform in size and shape with an average weight ranging from 1000 to 1500 g. The samples were free from external injuries and pathogenic infection were prevented by immersion in 0.01 % chlorinated water prepared from 5 % sodium hypochlorite. The samples were separated into three treatments, namely uncoated (control sample) and coated with stingless bee honey (SBH) concentrations of 1.0 % and 1.5 %, respectively. Each treatment consisted of twenty-five samples with five replicates.

SBH was obtained from the local farmer. Prior to the experiments, the SBH samples were stored in sterile, air-tight glass containers at room temperature to eliminate moisture absorption during the storage process. Edible coating of SBH at concentrations of 1.0 % and 1.5 % (w/v) was prepared by dissolving 1.0 and 1.5 g of SBH in 100 mL of distilled water containing 1 % of glycerol and Tween 20, respectively. The coating process was performed by dipping the papayas into the respective SBH concentrations for one minute. The samples were aired-dried for 2 h and single layer packed in commercial corrugated boxes prior to storage at 12 ± 1 °C and 85–90 % relative humidity for 12 d. The changes in the quality of papayas based on the physicochemical properties and respiration rate were recorded at three-day intervals.

2.2. Quality measurement of papayas

2.2.1. Physicochemical properties

The colour of the papaya peel was determined using a chromameter (Minolta CR300, Minolta Corp., Japan). The peel colour was expressed based on the chromaticity values of lightness (L*), chroma (C*), and hue (h*). The lightness of colour is represented by the L* coordinate with values ranging from 0 (black) to 100 (white); C* = (a*2 + b*2)1/2 represents the right triangle hypotenuse with values ranging from 0 (least intense) to 60 (most intense); h* refers to colour and the angle of the tangent of the c/h* as indicated by 0° (red-purple), 90° (yellow), 180° (blue-green), and 270° (blue) (Ali et al., 2011).

To determine fresh weight loss (FWL), five papayas from each replicate treatment were marked prior to storage and weighted using a digital balance (EK-600H, Japan). The fruits were weighed at the start of the experiment and the end of the storage period. The FWL is defined as the percentage loss of initial weight as shown in Eq. 1.

\[
\text{FWL} = \left(\frac{W_0 - W_f}{W_0}\right) \times 100
\]

Where W_0 is the average weight of the papaya at day 0 and W_f is the average weight of the same fruit at day t.

The firmness of the fruit was measured using the Instron universal testing machine (Model 5540, USA) and data measurements were collected using the compression mode. Five papayas in each replicate treatment group were measured using a probe with a diameter size of 50 mm at a speed of 50 mm/min and a load range of 100 N load cells. The compression force, expressed in Newtons (N), was measured at the maximum value of the peak force recorded.

During storage, the soluble solids content (SSC) of the pulp was analysed according to the methods described by Ali et al. (2011) and Mendy et al. (2019). The SSC (%) content was measured using a handheld refractometer (Model N-3000E, Atago, Japan) that was calibrated with distilled water before recording the measurements. Approximately 10 g of pulp tissues were homogenised in 40 mL of distilled water using a kitchen blender and filtered through cotton wool. A small drop of the filtrate was placed on the glass prism of the refractometer and the SSC measurements were recorded.

The titratable acidity (TA) was analysed according to the method described by Ali et al. (2011) using the titration method. Approximately 10 g of uncoated and coated papaya pulp tissue samples were homogenised in 40 mL of distilled water using a kitchen blender. The mixture was filtered through cotton wool and the filtrate samples (5 mL) were titrated with 0.1 N NaOH using one to two drops of 0.1 % phenolphthalein as an indicator until a pink colour was observed (pH 8.1). The titration results were expressed as a percentage of citric acid per 100 g of fresh fruit weight.

2.2.2. Respiration rate

The respiration rate of papaya was measured based on the method described by Ali et al. (2011). All the samples were subjected to internal gas concentration (carbon dioxide, CO2 and ethylene, C2H4) measurements, in which 1 mL of internal gas sample was withdrawn using a syringe after incubation for 2 h inside the respiration box. The gas samples were injected into a gas chromatography instrument (Clarus-500, Perkin–Elmer, USA) equipped with a stainless-steel column (Porapack R 80/100) and a molecular sieve (5A 45/60; 1/8 in. x 1.2 m) column with a thermal conductivity detector (TCD). The carrier gas, helium, was used at a flow rate of 3.0 mL·min⁻¹. The peak areas identified for the standard gas mixtures were measured before and after the analysis of the samples. The results were expressed as nmol kg⁻¹ s⁻¹ for CO2 and C2H4, respectively.

2.3. Microstructural and ultrastructural microscopy

Papaya peel cubes of 1.5 mm³ in thickness were cut from the centre section of each fruit. The samples were coated and mounted using a gold sputter and changes in the cuticular surface of the papaya were visualised under the scanning electron microscope (SEM) (HITACHI S-3400 N).

For the observation of ultrastructural changes, the papaya peel cubes were fixed in a solution containing 4 % glutaraldehyde at 4 °C for 2 d. The peel cubes were rinsed thrice with 0.1 M sodium cacodylate buffer (pH 7.6) for 30 min individually. The papaya peel cubes were post-fixed in a solution containing 1 % (w/v) osmium tetroxide at 4 °C for 2 h. The fixed papaya peel cubes were rinsed again in 0.1 M sodium cacodylate buffer solution (pH 7.6) three times for 30 min per cube. The cubes were dehydrated in a series of acetone concentrations, ranging from 35 to 100 % for three changes. The dehydrated papaya peel cubes were gradually infiltrated with acetone: resin mixture and subsequently
embedded into beam capsules containing 100 % resin prior to polymerisation at 60 °C for 2 d. Ultrathin cross-sections of the papaya peel cubes were cut with a diamond knife (Diatome 45, Switzerland) using a Richert-Jung Ultracut 2030 Microtome and mounted on the 200 mesh-sized copper grids. The sections were stained with uranylacetate and followed by lead citrate. The samples were examined using the Field Emission Electron Microscope (JEM-2100 F).

2.4. Data analysis and kinetic modelling

A two-way analysis of variance (ANOVA) was used to determine the statistical differences between the papaya samples coated with different SBH concentrations and storage days. The mean significant differences between the quality parameters for different SBH concentrations and storage days were compared using the Tukey test at a significance level of \( \alpha \leq 0.05 \). The correlations between each measurement such as FWL, firmness, respiration rate, SSC, and TA were evaluated using the Pearson correlation coefficient. Statistical analyses were performed using SAS 9.4 software (Version 9.4, SAS Institute, Cary, NC, USA). The kinetic modelling of the quality changes observed for papayas that were uncoated and coated with SBH concentrations of 1.0 % and 1.5 % during storage was described by zero and first-order kinetic models. The most accurate model-fitting kinetic analysis was performed according to the quality parameters at different SBH concentrations based on the storage time. The zero and first-order kinetic models were expressed as Eq. 2 and Eq. 3.

\[
\text{Zero order } = C = C_0 - kt \tag{2}
\]

\[
\text{First order } = C = C_0 \exp(-kt) \tag{3}
\]

Where \( C \) is the measured value for each quality parameter, \( C_0 \) is the initial value of the measured quality parameter, \( k \) is the rate constant, and \( t \) is the storage time (Laidler, 1984).

3. Results and discussion

3.1. Effect of SBH coating on quality changes in papaya

3.1.1. Physicochemical properties

In this study, all the papayas displayed a gradual loss of fresh weight (Fig. 1a). This observation could be related to the metabolic process during storage due to transpiration of fruit, thereby resulting in the shrivelling and deterioration of the fruit. Minimal fresh weight loss (FWL) was observed for papayas coated with 1.5 % of stingless bee honey (SBH), while the FWL for uncoated papayas was higher (\( P < 0.05 \)) than the coated samples (Table 1). The FWL was shown to decrease correspondingly with the increase in SBH concentration. Papayas coated with 1.5 % of SBH were able to maintain the FWL up to day 9, followed by an unexpected increase at day 12. It was possibly due to the hygroscopic effect of the higher concentrations of SBH coating. Therefore, SBH acts as an ideal coating agent that provides a partial barrier to water movement and reduces the moisture loss gradually from the surface of papaya. A similar finding was observed by García et al. (2010) for the FWL reduction in papayas that were coated with chitosan. Edible coatings were also shown to be effective in controlling water loss for other fruits such as guava (Silva et al., 2018), mango (Al-Qurashi and Awad (2018)), and avocado (Tesfay et al., 2017). Seymour et al. (1993) explained that the loss of water content in papaya was mainly through the peel. Therefore, the application of the edible coating on the fruit acts as a physical barrier to prevent water loss and modify the micro-atmosphere during storage (Sogvar et al., 2016).

Fruit firmness is one of the main attributes of the quality of fresh fruit production. Hence, the changes in fruit firmness during the transportation and storage period represent an important factor that should be taken into consideration. Fig. 1b indicates that the firmness in all the papaya samples decreased with the storage period although the coated papayas showed minimal changes. The changes in firmness throughout storage were significantly (\( P < 0.05 \)) lower for the uncoated samples as compared to the coated samples. The high value in firmness for the coated samples at 1.5 % SBH (43.18 N) was confirmed by the significant differences shown in the results of the Tukey’s test.
Table 1
Main and interaction effects of SBH coating, concentrations (Uncoated - 0 %, 1.0 %, and 1.5 %) and storage durations (0, 3, 6, 9, and 12 d) on colour, FWL, firmness, SSC, TA, respiration rate of papaya fruits at 12 ± 1 °C.

<table>
<thead>
<tr>
<th>% SBH Concentration (C)</th>
<th>L°</th>
<th>C°</th>
<th>h°</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>52.68 C</td>
<td>32.28 C</td>
<td>110.17 C</td>
</tr>
<tr>
<td>1.0</td>
<td>60.27 B</td>
<td>36.52 B</td>
<td>115.02 B</td>
</tr>
<tr>
<td>1.5</td>
<td>62.48 A</td>
<td>37.77 A</td>
<td>118.56 A</td>
</tr>
</tbody>
</table>

Storage duration (days), (SD)

| 0 | 61.92 A | 40.81 A | 125.96 A |
| 3 | 58.75 B | 36.39 B | 122.01 B |
| 6 | 57.63 C | 34.79 C | 115.60 C |
| 9 | 56.28 D | 35.51 D | 109.45 D |
| 12| 55.28 E | 31.24 E | 99.32 E |

C x SD

| * | * | * * | * * | * * | * * |

Different letters are significantly different at P < 0.05 by Tukey Test.

Table 2
Correlation on papaya quality attributes (FWL, Firmness, SSC, TA, CO2 and C2H4).

<table>
<thead>
<tr>
<th>FWL</th>
<th>Firmness</th>
<th>SSC</th>
<th>TA</th>
<th>CO2 (nmol kg⁻¹ s⁻¹)</th>
<th>C2H4 (nmol kg⁻¹ s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0.07***</td>
<td>0.74***</td>
<td>0.49***</td>
<td>0.94***</td>
</tr>
<tr>
<td>Firmness</td>
<td>1</td>
<td>0.02***</td>
<td>0.02***</td>
<td>0.62***</td>
<td>0.88***</td>
</tr>
<tr>
<td>SSC</td>
<td>0.74***</td>
<td>1</td>
<td>0.02***</td>
<td>0.02***</td>
<td>0.82***</td>
</tr>
<tr>
<td>TA</td>
<td>0.49***</td>
<td>0.02***</td>
<td>1</td>
<td>0.88***</td>
<td>0.94***</td>
</tr>
<tr>
<td>CO2</td>
<td>0.94***</td>
<td>0.02***</td>
<td>0.62***</td>
<td>1</td>
<td>0.59***</td>
</tr>
<tr>
<td>C2H4</td>
<td>0.94***</td>
<td>0.02***</td>
<td>0.68***</td>
<td>0.81***</td>
<td>1</td>
</tr>
</tbody>
</table>

*** Correlations are significant at α < 0.05.
combined with ginseng extract (Dong and Wang, 2018). Nevertheless, the decreasing rate of TA differed among the cultivars and storage environments.

The findings in this study also indicated that the SSC values correlated negatively with TA (Table 2). These findings were consistent with the study by Khaliq et al. (2015), in which the authors observed high SSC values that resulted in low TA values in mangoes coated with Arabic gum combined with calcium chloride. Besides, high SSC and low TA values in fruit were associated with pulp sweetness and fruit ripening. In addition to their biochemical reaction, the negative correlation observed between SSC and TA contributed to the fruit ripening, particularly in achieving the right balance of acidity and sugar in the fruit.

3.1.2. Colour changes

The colour changes for uncoated and SBH-coated papayas during

Fig. 2. Changes in (a) $L^*$, (b) $C^*$ and (c) $h^*$ value of uncoated and coated papaya at 1.0 % and 1.5 % SBH concentration.
storage at 12 ± 1 °C for 12 d are shown in Fig. 2. Ali et al. (2016) indicated that colour is an important factor for quality and consumer acceptance of papayas. In natural conditions, the colour changes from green to yellow continued throughout the storage period (Ali et al., 2011). The ANOVA results revealed that there were significant differences in the \(L^*\), \(C^*\) and \(h^*\) values at \(P < 0.05\) as shown in Table 1. The variation in the colour changes may be attributed to the differences in the ripening levels of papayas.

The loss of green colour in the fruit was due to the degradation of chlorophyll structure and \(\text{C}_2\text{H}_4\) bursting during storage. The principle agents responsible for this degradation were mainly due to the decrease in organic acids, high metabolic changes, oxidative system and chlorophyllases (Wills et al., 2007). The authors also described that the loss of colour depends on either one or all these factors acting in a sequence to destroy the chlorophyll structure. Similar findings were observed by Gomes et al. (2016) indicating that the colour change and ripeness of papayas occurred due to the increase in metabolism, thereby resulting in high \(\text{C}_2\text{H}_4\) production and low levels of organic acids.

Moreover, the disappearance of chlorophyll was also shown to be associated with the synthesis of the carotenoid pigments (Hashim et al., 2019), in which the carotenoid pigments became visible following the degradation of chlorophyll. It was also observed that the onset of ripeness led to the variation in pigments, ranging from greenish to yellowish in colour. This observation was supported by previous studies indicating that the biosynthesis of carotenoids (Wills and Widjanarko, 1995) and degradation of chlorophyll (Azevedo et al., 2008) resulted in changes to the skin colour of papayas from green to yellowish-orange and red. The ability of the edible coating to inhibit chlorophyll degradation has previously been reported in Indian jujube (Chen et al., 2012), sponge gourd (Han et al., 2014), and guava (Hong et al., 2012).

In this study, the trend in the colour changes was clearly observed as depicted in Fig. 3. Uncoated papayas showed a change in colour compared to papayas coated with SBH at concentrations of 1.0 % and 1.5 %. At the end of 12 d of storage, the uncoated papayas had values of \(L^* = 49.57\), \(C^* = 28.09\), and \(h^* = 92.78\). The uncoated papayas were yellow in colour due to the ripening process. Papayas coated with 1.0 % and 1.5 % SBH concentrations underwent gradual changes in their peel colour, as indicated by a decrease in \(L^*\), \(C^*\), and \(h^*\) values. There was a minimal change in the peel colour of papayas with 1.5 % SBH coating up to 6 d of storage with values of \(L^* = 63.81\), \(C^* = 36.33\), and \(h^* = 117.31\). While papayas with 1.0 % SBH coating displayed colour coordinate values of \(L^* = 62.04\), \(C^* = 38.15\), and \(h^* = 115.25\). This finding was in agreement with Ali et al. (2016) who investigated coated papayas and revealed a decreasing trend in colour development compared to uncoated papayas based on the \(L^*\), \(C^*\), and \(h^*\) values obtained after 21 d of storage.

The slow changes in colour development for SBH-coated papayas could be attributed to the low metabolism and reduced \(\text{C}_2\text{H}_4\) production. This observation was similar to a previous study by Latifah (1991) indicating that sucrose polyester coating was effective in modifying the atmosphere for Ekotsika papayas and resulted in slower changes to the skin colour of the fruit. In addition, Ali et al. (2011) described that the degradation of chlorophyll by the edible coating could be attributed to the modification of the atmosphere surrounding the fruit, thereby slowing down the production of \(\text{C}_2\text{H}_4\).

### 3.1.3. Changes in respiration rate

Several studies suggested that edible coatings can restrict changes in the internal gas atmosphere and intercellular spaces of fruits by covering the stomatal aperture (Basik et al., 2019; Jongsri et al., 2016). In this study, changes in the rate of \(\text{CO}_2\) and \(\text{C}_2\text{H}_4\) production during storage at 12 ± 1 °C were observed as shown in Fig. 4. The respiration rate of papayas coated with 1.0 % and 1.5 % SBH were significantly (\(P < 0.05\)) delayed and similar peaks for \(\text{CO}_2\) and \(\text{C}_2\text{H}_4\) were observed after 6 d of storage compared to the uncoated fruits. A gradual increase in the \(\text{CO}_2\) rate was observed for all the treatments during the 12 d with

**Fig. 3. Colour change of papaya peels in uncoated and after coating with SBH during storage at 12 ± 1 °C for 12 d.**

- **Storage time (days)**: Uncoated, 1.0 %, 1.5 %
- **Day 0**: 12.59 × 10⁻³ mmol kg⁻¹ s⁻¹ and 12.72 × 10⁻³ mmol kg⁻¹ s⁻¹ obtained for papayas coated with 1.0 % and 1.5 % SBH treatments, respectively. However, no major increment in \(\text{CO}_2\) rate was observed for the uncoated papayas during storage from day 9 to day 12. Additionally, the rapid accumulation of \(\text{CO}_2\) rate for the SBH-coated papayas may result in the reduction of Oxygen rate during storage. Moreover, Xu et al. (2018) revealed that \(\text{CO}_2\) accumulated in coated fruits due to the reduction in respiration rate and inhibition of physiological effects on the fruits.

On the other hand, the SBH coating on the papayas led to a reduction in \(\text{C}_2\text{H}_4\) rate, thus retarding the ripening process. As shown in this study, the \(\text{C}_2\text{H}_4\) production of uncoated fruits at 9 d was higher (8.92 × 10⁻³ mmol kg⁻¹ s⁻¹) compared to the fruits coated with 1.0 % and 1.5 % SBH treatments with a rate of 7.40 × 10⁻³ mmol kg⁻¹ s⁻¹ and 7.38 × 10⁻³ mmol kg⁻¹ s⁻¹, respectively. However, \(\text{C}_2\text{H}_4\) production was drastically reduced in uncoated papayas, while a slow decrease was observed for the coated fruits throughout the 12 d storage. Therefore, the reduction of \(\text{C}_2\text{H}_4\) production in papaya resulted in the delayed senescence.

The \(\text{CO}_2\) production was shown to be significant and negatively correlated with \(\text{C}_2\text{H}_4\) production (Table 2), thereby indicating that the increase in \(\text{CO}_2\) production rate led to low Oxygen concentrations and \(\text{C}_2\text{H}_4\) production. In a separate study, Ali et al. (2011) investigated the application of chitosan coating on papayas as a barrier to the gaseous exchange of \(\text{CO}_2\) and Oxygen. The authors found that the increase in \(\text{CO}_2\) rate during storage reduced the respiration rate and increased the shelf life of papayas. Furthermore, high \(\text{CO}_2\) production was shown to be necessary for stabilizing the respiration rate. Seminal contributions have been made by Martínez-Romero et al. (2006) indicating that the
rise in CO₂ rate (> 1 %) was thought to inhibit C₂H₄ synthesis during storage. The authors also noted that the presence of CO₂ surrounding the fruit may be sufficient to suppress the production of C₂H₄, and thus retard the ripening process.

Additionally, Wills et al. (2007) indicated that high CO₂ rate inhibited the breakdown of pectin substances and firmer textures of the fruits were retained for a longer period. The authors also noted that the increase in CO₂ facilitated the retention of organic acids in tomatoes. Therefore, CO₂ was significantly correlated with the firmness and TA in SBH-coated papayas. Furthermore, Hazrati et al. (2017) revealed that the major components of TA were organic acids that represented common substrates of enzymatic reactions in the respiration process. This observation indicated that the TA content was also an important factor in the respiration rate of fruits.

The findings of this study also indicated that the respiration rate positively correlated with SSC (Table 2). Hassanpour (2015) previously showed that the increase in SSC was correlated with a high respiration rate in fruits and senescence process. It was observed that the reduction in respiration rate resulted in lower rates of SSC in coated papayas. This finding was in agreement with Embuscado and Huber (2008), in which the authors reported that edible coating can control important gas exchanges such as Oxygen, CO₂, and C₂H₄ that are involved in the respiration process, thus delaying the ripening process and increasing SSC.

On the other hand, TA was shown to be significant and negatively correlated with the production of CO₂ and C₂H₄. These findings are in agreement with the study by Wills and Widjanarko (1995) indicating that low TA could be attributed to the metabolic changes, whereby the reduction of organic acids was due to the increased respiratory process. The present study revealed a high reduction in TA for uncoated papayas, thereby indicating that these papayas have a higher ripening rate compared to coated papayas.

3.2. Microstructural and ultrastructural changes

The effect of SBH coating on the surface characteristics of papayas was examined using SEM as shown in Figs. 5a–c. SBH coating at concentrations of 1.0 % and 1.5 % uniformly covered the peel surface as depicted in Figs. 5b and c, while some cracks and cleavages were observed between the cells in uncoated papayas (Fig. 5a). These results were similar to a study by Ayón-Reyna et al. (2017) who reported that the SEM microstructure of uncoated papaya showed the cracked layers on the surface morphology.

Thakur et al. (2019) indicated that starch coating on bananas provided a uniform coverage on the banana surface when analysed using SEM. Furthermore, the current study showed the SBH coating displayed a homogenous coating layer on the surface of papayas, thus slowing down the ripening process. It is also thought that the SBH coating may protect the stomata on the papaya peels and reduce the respiration rate. The results observed were consistent with the study by Jongsri et al. (2016) who observed that the low molecular weight of chitosan coating conferred protection and covered the stomata of mango peels, thus
delaying the ripening process during the storage period. In addition, Deng et al. (2017) demonstrated that the non-homogeneous coating on the fruit surface may potentially increase the mass transfer across the fruit surface, thereby leading to an increased respiration rate and fungal infection. In this study, the coated papayas maintained a low respiration rate by slowing down the Oxygen and C2H4 production.

The ultrastructural features of mitochondria in papaya peel tissues were observed using Field Emission Electron Microscopy after 12 d during storage. The main role of mitochondria is to generate energy for the cell and this cellular organelle is vulnerable to different stress conditions (Khaliq et al., 2015). Recently, Lin et al. (2018) suggested that the changes in respiratory activities of fruits are reflected by the functional characteristics of mitochondria. In this study, the ultrastructural changes in coated and uncoated papayas are shown in Figs. 5d–f. The ultrastructure of mitochondria in uncoated papayas revealed that the entire structure was almost ruptured and the mitochondria membrane was damaged (Fig. 5d).

In contrast, the ultrastructure image of mitochondria in papayas coated with 1.0 % SBH was observed as normal, while slight changes were observed in the mitochondrial membrane (Fig. 5e). In papayas coated with 1.5 % SBH, the entire structure of the mitochondria appeared to be well located, in which the mitochondria membrane was intact (Fig. 5f). These observations were similar to the study by Khaliq et al. (2015) who demonstrated that Arabic gum coating combined with calcium chloride protected the mitochondrial structure in coated mango samples, while the structure of the mitochondria membrane in control samples was ruptured after 28 d of storage at 6 °C. Besides, a previous study by Li et al. (2012) indicated that the mitochondrial structure in methyl jasmonate-treated cucumbers stored at low temperatures was well preserved. The authors also mentioned that the mitochondrial structures of the control samples were damaged after 49 d of storage.
Mitochondria generate energy for the cell and execute various functions during the fruit respiration process. Moreover, any form of abnormalities in the mitochondrial structure will affect fruit qualities such as fruit firmness and change in colour. In this study, the uncoated papayas displayed a fragmented mitochondrial structure due to senescence and deterioration of the fruits, while papayas coated with 1.0 % and 1.5 % of SBH exhibited delayed ripening and the physicochemical qualities of those papayas were maintained. Therefore, it is evident that SBH coating may protect the ultrastructural features of mitochondria during storage.

3.3. Kinetics of quality changes in papayas

The kinetic parameters for the quality changes in uncoated and coated papayas are shown in Table 3. For fruit firmness, the R² values of uncoated samples were 0.808 and 0.821 for zero-order and first-order kinetic models, respectively. In contrast, the R² values for papayas coated with 1.0 % of SBH were 0.924 and 0.95, while papayas coated with 1.5 % of SBH showed slightly lower R² values of 0.732 and 0.771 for zero-order and first-order kinetic models, respectively. Additionally, the rate constant for firmness in zero-order and first-order kinetic models decreased from 0.204, 0.046, and 0.040 (day⁻¹) to 0.063, 0.011, and 0.009 (day⁻¹) for uncoated, 1.0 %, and 1.5 % SBH concentrations, thereby indicating the higher efficiency of edible coating. Similar results with a decreasing rate constant were found in the kinetic models for firmness and moisture loss in tomatoes during a storage period of up to 20 d at various temperatures (Van Dijk et al., 2006).

The FWL based on the kinetic parameters was in agreement with the first-order kinetic model based on the higher R² values obtained compared to the values for the zero-order kinetic model (Table 3). The FWL for uncoated papayas was indicated by R² values of 0.856 and 0.892 for zero-order and first-order kinetic models, respectively. On the other hand, papayas coated with 1.0 % of SBH obtained R² values of 0.798 and 0.897, while papayas coated with 1.5 % of SBH achieved the highest R² values of 0.964 and 0.940 for the zero-order and first-order kinetic models, respectively. Additionally, the rate constant of FWL for zero-order and first-order kinetic models increased from -0.972, -0.673, and -0.610 (day⁻¹) to -0.147, -0.126, and -0.120 (day⁻¹) for uncoated, 1.0 %, and 1.5 % SBH concentrations. The FWL under various conditions was also shown to be associated with the storage period at different temperatures to reduce spoilage and withering (Maftoonazad and Ramaswamy, 2008). In another study by Maftoonazad and Ramaswamy (2019), the zero-order kinetic model showed high R² values of 0.981 and 0.995 for uncoated and coated lime fruits at 10 °C, respectively.

The Arrhenius fractional conversion kinetic model was successfully fitted to the colour parameters of L*, C*, and h* values (Table 3). The highest R² value obtained for L*, C*, and h* in uncoated papayas were higher than 0.700 for the zero-order and first-order kinetic models, respectively. In contrast, the results for the colour parameters of papayas coated with 1.0 % and 1.5 % SBH concentrations were higher, with R² values greater than 0.800 for both kinetic models. Maftoonazad and Ramaswamy (2019) recently reported that the kinetic models demonstrated high performance for lime fruits coated with peptin, resulting in R² values greater than 0.900 for a*, b*, C*, and L* using the Arrhenius law approach. Moreover, a study by Ali et al. (2017) demonstrated that the prediction model for seedless watermelon showed R² values greater than 0.900 for the colour parameters (L*, a*, b*, C*, and h*) respectively in tomatoes. It was shown that the model adequacy based on the colour parameters was due to chilling injury, exposure to external damage and deterioration. Hence, the results may vary due to the differences in temperatures, cultivars, storage days, and ripening stages.

The production of C₂H₄ and CO₂ in uncoated papayas displayed R² values of 0.721 and 0.960 as well as 0.797 and 0.891 for zero-order and first-order kinetic models, respectively (Table 3). On the other hand, the R² values of C₂H₄ and CO₂ production in papayas coated with 1.0 % and 1.5 % SBH concentrations were greater than 0.730 for both kinetic models. Similar results were also observed for quality changes in the respiration rate of mangoes (Moalemian et al., 2012), strawberries (Abdi et al., 2017; Treviño-Garza et al., 2015), and raspberries (Guerreiro et al., 2015) based on the edible coating used.

In contrast, the R² values obtained for SSC was 0.772, 0.960, and 0.814 (zero-order model) as well as 0.868, 0.844, and 0.762 (first-order model) for uncoated, 1.0 %, and 1.5 % SBH concentrations, respectively. TA also displayed R² values greater than 0.600 for uncoated, 1.0 %, and 1.5 % SBH-coated papaya samples. The decrease in TA observed for all the treatments was associated with the biochemical reaction during the ripening process of the fruit. For instance, the reduction in TA could be due to the low O₂ utilisation in the respiratory process (Maftoonazad and Ramaswamy, 2019). Thus, the changes in SSC and TA were considered to be well described by both the kinetic models and their values were significantly influenced based on the coating treatments.

4. Conclusions

In conclusion, a kinetic model that describes the quality changes in uncoated and coated papayas is presented in this study. Specifically, the quality changes in firmness, FWL, colour parameters (L*, a*, b*, C*, and h*), respiration rate, SSC, and TA were satisfactorily described by zero and first-order kinetic models. The statistical analysis for the quality changes in uncoated and coated papayas exhibited significant differences among the investigated parameters (P < 0.05). The quality of papayas after harvest was maintained by the SBH coating that acted as a physical barrier to minimise water loss and respiration rate, thereby reducing FWL, increasing SSC, and decreasing TA. Moreover, only slight ultrastructural changes in the mitochondria were observed in coated papayas as compared to the uncoated samples. It is evident that 1.5 % SBH coating has great potential in delaying the ripening process during fruit storage and addressing the challenges faced due to post-harvest losses. It is envisaged that the experimental data from this study

Table 3

<table>
<thead>
<tr>
<th>Concentration</th>
<th>Parameter</th>
<th>Zero-order model</th>
<th>First-order model</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>k (day⁻¹)</td>
<td>R²</td>
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<td>Uncoated</td>
<td>Firmness</td>
<td>0.204</td>
<td>0.808</td>
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<tr>
<td></td>
<td>FWL</td>
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<td>0.856</td>
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<tr>
<td></td>
<td>C₂H₄</td>
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<td>0.721</td>
</tr>
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<td></td>
<td>CO₂</td>
<td>-1.367</td>
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</tr>
<tr>
<td></td>
<td>L*</td>
<td>0.908</td>
<td>0.715</td>
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<td></td>
<td>C*</td>
<td>0.869</td>
<td>0.969</td>
</tr>
<tr>
<td></td>
<td>h*</td>
<td>2.553</td>
<td>0.893</td>
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<tr>
<td></td>
<td>SSC</td>
<td>-0.358</td>
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<td>TA</td>
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<tr>
<td>1.0 % Firmness</td>
<td>FWL</td>
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<td>0.924</td>
</tr>
<tr>
<td></td>
<td>C₂H₄</td>
<td>-0.673</td>
<td>0.798</td>
</tr>
<tr>
<td></td>
<td>CO₂</td>
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<tr>
<td></td>
<td>L*</td>
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</tr>
<tr>
<td></td>
<td>C*</td>
<td>0.632</td>
<td>0.961</td>
</tr>
<tr>
<td></td>
<td>h*</td>
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<td>0.911</td>
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<tr>
<td></td>
<td>SSC</td>
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<td>TA</td>
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<tr>
<td>1.5 % Firmness</td>
<td>FWL</td>
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<td>0.732</td>
</tr>
<tr>
<td></td>
<td>C₂H₄</td>
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<td>0.964</td>
</tr>
<tr>
<td></td>
<td>CO₂</td>
<td>-1.406</td>
<td>0.998</td>
</tr>
<tr>
<td></td>
<td>L*</td>
<td>0.534</td>
<td>0.917</td>
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<tr>
<td></td>
<td>C*</td>
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<td></td>
<td>h*</td>
<td>1.851</td>
<td>0.920</td>
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<tr>
<td></td>
<td>SSC</td>
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</tr>
<tr>
<td></td>
<td>TA</td>
<td>0.063</td>
<td>0.954</td>
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</table>
would be useful for papaya quality estimation during storage as well as for fresh fruit distribution in retail sectors.

Author contribution statement

Bernard Maringgal carried out the literature review, methodology, experiment, and performed the main writing part. Norhashila Hashim supervised the study by providing financial assistance sourced from her funded research grant, provided the concept and structure of the manuscript and supervised the study as well as giving her advice on the manuscript. Intan Syafinaz Mohamed Amin Tawakkal, Mahamd Tengku Muda Mohamed, and Muhammad Hazwan Hamzah worked on the manuscript, and in particular reviewed the content and revised the text. Maimunah Mohd Ali helped and guided on the software and kinetic quality changes. Mohd Faizol Haffiz Ab Razak assisted the laboratory work.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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