



Modelling the kinetics of physicochemical changes in *Terung Asam* (*Solanum lasiocarpum* Dunal.) during storage

Sophia Ann Suring^a, Bernard Maringgal^{a,b,*}, Norhashila Hashim^{c,d}, Nurazwin Zulkifli^e

^a Faculty of Resource Science and Technology, Universiti Malaysia Sarawak, 94300 Kota Samarahan, Sarawak, Malaysia

^b UNIMAS Agro Research Center, Universiti Malaysia Sarawak, 94300 Kota Samarahan, Sarawak, Malaysia

^c Department of Biological and Agricultural Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia

^d SMART Farming Technology Research Centre (SFTRC), Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia

^e Department of Agriculture Malaysia, 62624 Putrajaya, Malaysia

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ABSTRACT

This research studied the structural changes and physicochemical quality and in *Terung Asam* (*Solanum lasiocarpum* Dunal) during a 28-day ambient storage period at Day 0, Day 7, Day 14, Day 21 and Day 28. Colour values (L^* , C^* , h^*), soluble solid content (SSC), fresh weight loss (FWL), fruit firmness, total chlorophyll content (TCC) and pH were the parameters assessed. The peel's ultrastructural and microstructural image characteristics were also examined. Significant ($p < 0.05$) physicochemical deterioration was observed, particularly in firmness, FWL, and TCC, which followed zero-order kinetic behaviour with high model fits, recording R^2 values of 0.986, 0.988, and 0.998 and RMSE values of 0.089, 0.731, and 0.062, respectively. In contrast, h^* followed first-order kinetics, with $R^2 = 0.829$ and RMSE = 4.519, indicating that the colour shift during storage was more dependent on the remaining pigment intensity. In agreement with senescence-related changes, based on cell wall loosening, mitochondrial and chloroplast disintegration, and stomatal deformation identified through microscopic image analysis, it can be concluded that progressive cellular degradation took place. Through the established kinetic models, it was possible to obtain insights into the rate of quality degradation, that provided a predictive framework for postharvest behaviour. These results yielded in improved shelf-life estimation and storage management strategies for *Terung Asam*, to support its marketability, postharvest handling, and sustainable utilisation.

1. Introduction

Solanum lasiocarpum Dunal., commonly known as *Terung Asam*, is an indigenous tropical fruit widely consumed in Sarawak and other parts of Malaysia [1]. This perennial plant thrives in Borneo's wet tropical climate and can grow up to 1.5 m in height [2]. As a member of the Solanaceae family, it is closely related to tomatoes and peppers, and is valued in traditional meat-based dishes for its firm texture and distinctive acidic, tangy flavour [3]. Beyond its culinary importance, *Terung Asam* is also recognised for its nutritional and medicinal value, particularly due to its vitamin C, potassium, calcium and iron contents [4,5]. During maturation and storage, the fruit undergoes a visible colour transition from green to yellow or orange [6], mainly associated with chlorophyll a and b degradation, as similarly reported in other *Solanum* species where oxidative and enzymatic activities accelerate chlorophyll

breakdown during storage [7,8]. Hamzah et al [9] also reported significant colour changes in *Terung Asam* after 11 days of storage, indicated by decreasing L^* values and increasing a^* values, reflecting darkening and redness development. As storage progresses, yellowing may be followed by browning due to polyphenol oxidation and the formation of dark-coloured pigments.

As a climacteric fruit, *Terung Asam* undergoes rapid physiological and biochemical changes after harvest, which can shorten shelf life, reduce marketability and accelerate quality deterioration under ambient storage conditions. Postharvest deterioration in climacteric fruits is mainly driven by internal metabolic processes such as respiration and ethylene production, together with external factors such as moisture loss and structural degradation [10,11]. These processes result in measurable changes in physicochemical attributes, including firmness, total soluble solids, titratable acidity, pH, chromaticity and weight loss [12,

* Corresponding author.

E-mail address: mbernard@unimas.my (B. Maringgal).

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13]. Storage temperature and relative humidity strongly influence the rate of these biochemical changes and the progression of senescence. Gelaye [14] emphasised that appropriate temperature and humidity management can slow ripening, reduce respiration rate, minimise disease incidence and prevent dehydration in climacteric fruits. In *Solanum* fruits, ambient storage has been associated with moisture loss, increasing acidity, nutrient degradation and reduced marketability [15], with quality changes influenced by interactions between storage duration and mineral composition [16,17]. Although cold storage at 10°C has been reported to preserve the fruit for up to 30 days [18], unripe fruits may have a shorter storage life due to chilling injury, with prolonged storage leading to surface wrinkling, dark brown spotting, tissue shrinkage and softening [5]. Therefore, while postharvest quality losses in *Terung Asam* have been reported, systematic and predictive studies on its deterioration remain limited. In the present study, ambient storage was selected to represent common postharvest exposure during local handling, transport, temporary holding and market display, especially in situations where cold-chain facilities are limited or not consistently applied. Although refrigerated storage can delay deterioration, establishing the deterioration pattern under ambient conditions is important as a baseline for understanding the natural progression of ripening and senescence in *Terung Asam*.

Kinetic modelling provides a useful framework for quantifying the rate and extent of postharvest quality degradation [19]. By describing changes in physicochemical parameters as time-dependent reactions, kinetic models can support shelf-life prediction and help identify dominant deterioration patterns. Zero- and first-order models are commonly applied in postharvest studies because they are interpretable and suitable for practical storage durations. Mohd Ali et al [20], for instance, modelled quality changes in climacteric pineapple fruits stored at different temperatures and showed that firmness and moisture content were effective indicators for shelf-life prediction, with first-order kinetic models producing high coefficients of determination. Similarly, Al-Dairi and Pathare [21] reported that postharvest changes in tomato, including weight loss, firmness and colour attributes, were well described using zero- and first-order kinetic models, although the best-fitting model varied depending on storage temperature and quality attribute. However, the application of kinetic modelling to underutilised climacteric fruits such as *Terung Asam* remains limited, particularly when combined with structural evidence that can explain the biological basis of quality deterioration.

In addition to physicochemical measurements, fruit quality during storage is closely associated with structural integrity at the cellular and subcellular levels. Prolonged storage can cause cellular degradation, especially in the fruit peel, including the collapse of epidermal and subepidermal tissues, which affects texture, visual quality, shelf life and marketability [22,23]. Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) provide detailed observations of tissue collapse, cell wall degradation and membrane disintegration during ripening and senescence. For example, Li et al [24] used SEM and TEM to examine banana pulp during ripening and reported progressive starch granule degradation, cell wall collapse, middle lamella loss and changes in pulp ultrastructure associated with fruit softening. Therefore, integrating kinetic modelling with microstructural and ultrastructural observations can strengthen postharvest quality evaluation by linking measurable quality changes with the underlying structural processes that govern fruit senescence.

Accordingly, this study aims to (i) evaluate the physicochemical changes of *Terung Asam* during ambient storage, (ii) model the kinetics of key quality attributes using zero- and first-order reaction models, and (iii) identify the microstructural and ultrastructural changes associated with fruit ripening and senescence using SEM and TEM. By combining kinetic analysis with structural evidence, this study provides a more concise and mechanistic understanding of postharvest deterioration in *Terung Asam* and contributes foundational data to support improved storage management, shelf-life estimation and sustainable utilisation of

this underutilised tropical climacteric fruit.

2. Materials and methods

2.1. Fruit samples preparation

In order to make sure there's an immediate access after harvest, through direct procurement with a local farmer, a total of 150 *Terung Asam* fruits were procured from the Agricultural Market Bandar Riyal in Samarahan, Sarawak (N1°27'30.4", E110°24'36.7"). As per the description by Soon and Ding [5] and Suring et al [1], based on uniformity in firmness, colour and skin texture as well as the absence of physical defects, the fruits were selected. Residual moisture as well as surface debris were removed gently before experimentation using a lint-free absorbent cloth.

The fruits were randomly allocated into five storage intervals, namely Day 0, Day 7, Day 14, Day 21 and Day 28, with 30 fruits assigned to each interval. All fruits were at the green maturity stage at the onset of storage, and ripening stages were evaluated based on skin colour, as described in previous studies [1,25,26]. The fruits were stored under controlled ambient conditions at $25 \pm 2^\circ\text{C}$ and 65–75% relative humidity for 28 days.

Ambient storage was selected to simulate common local postharvest handling and market-display conditions, where fruits may be temporarily held without refrigeration before consumption, processing or sale. The 28-day storage period was chosen to allow the progression of quality changes to be monitored across early ripening, senescence, and advanced deterioration stages, thereby providing sufficient time-dependent data for kinetic modelling of postharvest quality loss.

The experimental design was based on independent sampling across storage intervals. Fruits allocated to each storage duration were treated as independent samples, and each individual fruit was considered one experimental unit and one biological replicate. Therefore, the same fruit was not treated as a repeated observation across all storage durations. Prior to storage, each fruit was placed in an uncoated box without plastic or wax lining to allow natural airflow and minimise moisture accumulation, which could otherwise influence the storage conditions.

As depicted in Fig. 1, before storage, in order to allow natural airflow and minimise moisture accumulation, each fruit was re-cleaned again and placed in an uncoated box without plastic or wax linings, which could otherwise influence temperature measurement.

2.2. Physicochemical properties of *Terung Asam*

2.2.1. Determination of fruit colour quality

Using a calibrated colorimeter (3nh NR110 Precision Colourimeter, Shenzhen ThreeNH Technology Co., Ltd., Shenzhen, China) under controlled laboratory conditions, fruit colour was analysed as per the method of Kasampalis et al [27]. All measurements were conducted at ambient room temperature ($25 \pm 2^\circ\text{C}$) under standardized illumination using a D65 light source. The instrument was calibrated against a white standard reference plate prior to each measurement session.

Colour measurements were obtained at 7-day intervals, corresponding to five sampling points over storage period. At each sampling point, colour readings were taken from 30 individual *Terung Asam* stored within single box, and mean values were subsequently calculated. In total, 150 colour measurements were collected across all sampling points.

The colour parameters recorded included L^* , C^* , and h^* . The L^* parameter represent lightness, ranging from 0 (black) to 100 (white), as defined by López Camelo and Gómez [28]. Chroma (C^*) indicates colour saturation or intensity, while hue (h^*) describes the perceived colour tone [29]. Collectively, these parameters describe the three-dimensional colour space, with L^* corresponding to lightness, C^* to colour intensity, and h^* to the tonal attribute of the fruit surface.

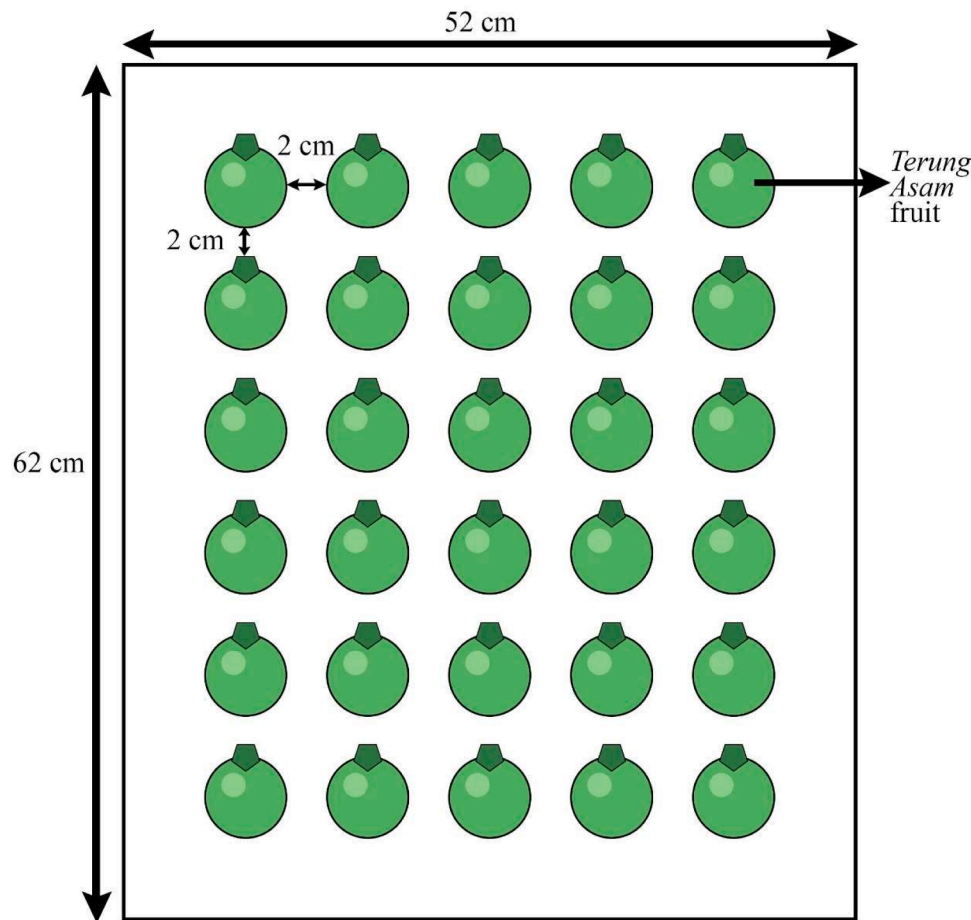


Fig. 1. Schematic arrangement of Terung Asam fruits in an uncoated box.

2.2.2. Determination of fruit firmness

Fruit firmness was measured using a digital penetrometer (GY-M15 Digital Fruit Hardness Tester, 0.4–30 kgf cm⁻², Shahe Measuring Instrument Co., Ltd., Hebei, China), and the results were expressed in Newtons (N). Initial firmness measurements were obtained immediately upon arrival of the fruits at the laboratory, after which the remaining samples were stored under ambient conditions at 25 ± 2°C, in accordance with Harker et al [30]. Subsequent firmness assessments were conducted at 7-day intervals over 28-day storage period. At each sampling point, a single firmness measurement was taken from each of the 30 fruits, and the mean value was calculated to represent the firmness of the sample.

2.2.3. Determination of fruit fresh weight loss

Fresh weight loss was determined by weighing a total of 150 *Terung Asam* using a digital balance (FX-300i Precision Balance, 320 g × 0.001 g, A&D Company, Tokyo, Japan), following the methods described by Andrade et al [31] and Ilea et al [32]. Prior to firmness evaluation, all fruits were equilibrated at room temperature for 24 hours, in accordance with the procedure outline by Harker et al [30]. Fresh weight loss was expressed as percentage and calculated using Equation (1), as describe by Parven et al [33]:

$$(\%)FWL = \frac{w^0 - w_t}{w^0} \times 100 \quad (1)$$

where w^0 represents the average initial weight of the fruits at day 0, and w_t represents the average weight of the same fruits at time t . Measurements were conducted at 7-day intervals over a 28-day storage period, corresponding to five sampling points. Thirty individuals *Terung Asam*

were weighed at every sampling point, and the mean values were computed in order to represent the sample.

2.2.4. Determination of total soluble solid content

Using a digital handheld refractometer, the total soluble solids (TSS) content of *Terung Asam* was determined (HI96802 Digital Refractometer for Sugar Analysis, Hanna Instruments, Woonsocket, RI, USA) [17,34,35]. Fresh fruits were washed with distilled water, peeled, and using a blender, the edible portion was homogenized. In order to obtain a juice extract that is clear, the homogenate obtained was filtered using cheesecloth. In the refractometer prism, a few drops of the juice were placed and the TSS was recorded as degrees Brix (°Brix). Before every measurement session, the refractometer was calibrated with distilled water.

Measurements were taken at 7-day intervals over a 28-day storage period, five sampling points were obtained. The juice was prepared from 30 individual *Terung Asam*, at each sampling point. The recorded TSS values were averaged in order to obtain the sample's mean value.

2.2.5. Determination of total chlorophyll content

The total chlorophyll content of *Terung Asam* was determined using spectrophotometrically [36,37]. Chlorophyll pigments were extracted from the fruit peel by homogenizing the tissue in 80% acetone, followed by centrifugation to obtain a clear supernatant. Absorbance of the extract was measured wavelength of 646.8 nm and 663.2 nm using a UV-Vis spectrophotometer (Cary 60 UV-Vis Spectrophotometer, Agilent Technologies, Santa Clara, CA, USA). The total chlorophyll concentration (mg/L) was calculated using the following Equations (2)–(4), in accordance with the method described by Lichtenthaler and Wellburn

[38]:

$$\text{Chlorophyll } a = 12.21 \times [A_{663.2} - (0.5 \times A_{646.8})] \times \frac{V}{W} \quad (2)$$

$$\text{Chlorophyll } b = 20.13 \times [A_{663.2} - (0.3 \times A_{646.8})] \times \frac{V}{W} \quad (3)$$

$$\text{Total Chlorophyll} = \text{Chlorophyll } a + \text{Chlorophyll } b \quad (4)$$

where $A_{663.2}$ and $A_{646.8}$ were the absorbance values, V is the volume of solvent used for extraction in milliliter, mL and W is the weight of *Terung Asam* peel in grams, g. Results were expressed as milligrams of chlorophyll per 100g of extract. Measurements were conducted at 7-day intervals over a period of 28-day storage period, corresponding to five sampling points. At each sampling point, peel samples were collected from 30 individual *Terung Asam*, and the chlorophyll content values were averaged to obtain the mean value for each sampling point.

2.2.6. Determination of fruit pH level

The pH content of *Terung Asam* was determined following standard fruit quality analysis procedure. Fresh fruits were thoroughly washed with distilled water, peeled, and the edible portion was homogenized using a blender. The homogenate was filtered to obtain a clear juice extract, and the pH was measured directly using a calibrated digital pH meter (edge® Dedicated pH/ORP Meter HI2002, Hanna Instruments, Woonsocket, RI, USA). The electrode was rinsed with distilled water between measurements to prevent cross-contamination. All measurements were conducted at room temperature, and the pH meter was calibrated prior to analysis using standard buffer solutions of pH 4.0 and 7.0. Measurements were performed at 7-day intervals over a 28-day storage period, corresponding to five sampling points. At each sampling point, juice extracts were prepared from 30 individual *Terung Asam*, and the pH values were averaged to obtain the mean for each sampling point. The fruit preparation and pH determination procedures were adapted from AOAC [34].

2.3. Microstructural and ultrastructural microscopy

Peel samples of *Terung Asam* were cut into small cubes measuring approximately $5 \times 5 \times 2$ mm and prepared for both SEM and TEM. For SEM analysis, peel cubes were fixed in 2.5 % glutaraldehyde prepared in 0.1 M sodium cacodylate buffer (pH 7.2) for 2-4 hours at 4°C. The samples were then rinsed in the same buffer and post-fixed in 1 % osmium tetroxide for 1-2 hours. Following fixation, samples were dehydrated through a graded ethanol series and dried using critical-point drying. The dried specimens were mounted on aluminium stubs and sputter-coated with a thin layer of gold-palladium prior to imaging. SEM observations were performed using a HITACHI S-3400N SEM (Japan) [39].

For TEM, peel cubes were fixed in glutaraldehyde and osmium tetroxide as described above, followed by en bloc staining with uranyl acetate. The samples were subsequently dehydrated through a graded ethanol series, transitioned with propylene oxide and embedded in epoxy resin. Ultrathin sections (~70 nm) were cut using a diamond knife (Diatome 45, Switzerland) on a Reichert Jung Ultracut 2030 Microtome and mounted on copper grids. The sections were stained with uranyl acetate as well as lead citrate [40,41] and inspected under a TEM equipped with a Gatan ORIUS CCD camera. From both SEM and TEM analyses, micrographs were obtained at 7-day intervals (Days 7, 14, 21, and 28) to monitor progressive changes in peel microstructure as well as ultrastructure during storage [42,43].

2.4. Statistical analysis and kinetic modelling

Based on the sampling arrangement described in Section 2.1, storage duration was treated as the main factor in the experimental design.

Fruits allocated to each storage interval were treated as independent samples, and each individual fruit was considered one experimental unit and one biological replicate. Accordingly, each storage duration was analysed as a separate independent group in the statistical analysis.

Experimental data were analysed using IBM SPSS Statistics (Version 27.0.1.0). Prior to one-way analysis of variance (ANOVA), normality and homogeneity of variance were assessed using the Shapiro-Wilk test and Levene's test, respectively. In order to evaluate differences among the mean values of colour parameters like L^* , C^* , h^* , firmness, pH, fresh weight loss, soluble solid content, and total chlorophyll content, analysis of variance (ANOVA) was conducted. When significant effects were detected, mean separation was performed using the Least Significant Difference (LSD) test at a significance level of $p < 0.05$.

Kinetic modelling was employed to describe the degradation behaviour of selected quality attributes throughout the 28-day storage period. Zero-order and first-order kinetic models were applied to estimate reaction rate constants (k) and coefficients of determination (R^2) for L^* , C^* , h^* , firmness, fresh weight loss, soluble solid content, total chlorophyll content, and pH. These two models were selected because they are commonly used to describe postharvest quality changes that may either progress at an approximately constant rate or vary according to the remaining concentration or intensity of the measured attribute [44]. Linearized forms of the kinetic equations were fitted to the experimental data characterize and predict time-dependent changes in fruit quality during storage.

The zero-order model was applied to quality attributes that changed at a relatively constant rate during storage, regardless of the remaining value of the attribute. The model was expressed as:

$$Q_t = Q_0 \pm kt \quad (5)$$

where Q_t is the measured value of each quality parameter at storage time, t , Q_0 is the initial value of the measured quality parameter, k is the reaction rate constant, and t is the storage time in days. The negative form, $Q_t = Q_0 - kt$ was used for decreasing quality attributes, while the positive form, $Q_t = Q_0 + kt$, was used for increasing quality attributes such as FWL.

The first-order model was used for quality attributes in which the rate of change was dependent on the remaining concentration or intensity of the attribute. The model was expressed as:

$$Q_t = Q_0 e^{-kt} \quad (6)$$

and its linearised form was expressed as:

$$\ln Q_t = \ln Q_0 - kt \quad (7)$$

For zero-order kinetics, Q_t was plotted against storage time, while for first-order kinetics, $\ln Q_t$ was plotted against storage time. The reaction rate constant (k) was derived from the slope of the fitted regression line. For FWL under first-order modelling, Day 0 was excluded from logarithmic transformation because the initial FWL value was 0%, and $\ln(0)$ is undefined.

Model suitability was assessed using the coefficient of determination (R^2), residual analysis, and root mean square error (RMSE). Residuals were calculated as the difference between observed and predicted values at each storage interval. RMSE was then calculated to quantify the average prediction error of each model using the following equation:

$$RMSE = \sqrt{\frac{\sum (Q_{obs} - Q_{pred})^2}{n}} \quad (8)$$

where Q_{obs} is the observed value, Q_{pred} is the predicted value generated from the fitted kinetic model, and n is the number of storage time points. RMSE values were expressed in the original units of each parameter; therefore, RMSE was compared only between zero-order and first-order models within the same quality attribute and not across different parameters [45]. The preferred kinetic model was selected based on a

combination of higher R^2 , lower RMSE, residual behaviour, consistency with the observed storage trend, and biological plausibility of the deterioration process.

Although AIC is widely used for comparing candidate models by considering model fit and complexity [46,47], it was not applied as an additional selection statistic in this study because only five storage time points were available and the comparison was limited to two pre-defined kinetic models with comparable model complexity. Independent external validation was also not performed because the study was based on one ambient storage dataset. Therefore, the kinetic models are interpreted as preliminary predictive models, and future studies should validate them using independent fruit batches and additional storage temperatures.

3. Results and discussion

3.1. Physicochemical changes of Terung Asam

3.1.1. Fruit colour quality

The colour attributes of *Terung Asam* fruit during 28 days of storage were quantified using the CIE L^* , C^* and h^* colour parameters, as presented in Table 1. The fruit colour gradually shifted from green to yellow over the storage period under ambient conditions and this shows ripening progression as well as the onset of senescence. Based on the mean values, the colour transition followed a non-linear and stage-dependent pattern, where early storage was associated with increased brightness and colour saturation, followed by reduced lightness and chroma during prolonged storage. In contrast, the h^* value showed a clearer decreasing trend, indicating a progressive shift from green or yellow-green tones towards yellowing. This transition, which has been widely reported in *Solanum* species, is primarily driven by chlorophyll degradation accompanied by carotenoid accumulation during fruit maturation [26].

As presented in Table 1, a distinct temporal pattern was depicted by the fruit surface lightness (L^*). From 52.97 on Day 0, the L^* values increased to a maximum of 56.73 on Day 7, and by Day 14, a slight decrease to 56.02 was observed. A pronounced decline was observed next, with L^* decreasing to 49.02 and 48.28 on Day 21 and Day 28, respectively (Table 1). Similar pattern in reductions of L^* have been observed in climacteric tropical fruits and this happens because of pigment transformation during ripening, that leads to a drop in visual quality and also surface brightness [48]. Similar patterns have been observed in citrus fruits, papaya and mango when they were stored for an extended period of time whereby reducing lightness were observed along with senescence and peel aging [23,49,50]. These outcomes ascertain L^* as a reliable metric of ripening advancement as well as postharvest quality deterioration in *Terung Asam*.

Chroma (C^*) that represents colour saturation saw a complementary pattern during storage. An increase in C^* values from 39.28 to 44.43 on Day 0 to Day 7 was observed and by Day 14, this value peaked at 44.63 and this shows enhanced colour vividness during early ripening. After that, chroma dropped significantly to 38.46 and 35.72 from Day 21 to Day 28 (Table 1), indicating that colour dullness happened progressively

during extended storage period. Under ambient storage conditions in most climacteric fruits, it is found that this decline is consistent with senescence-related pigment degradation and moisture loss [51–53], and this shows C^* as a sensitive metric of postharvest colour degradation.

The h^* value (h^*) as shown in Table 1, that describes perceived colour tone, revealed a declining pattern overall during storage. On Day 0, the initial h^* value of 97.29 that corresponds to a green to yellow-green hue, reduced dramatically on Day 7 to 80.05 and dwindled steadily to 70.96 on Day 14 and 66.64 on Day 21. However, the reading increased a little on Day 28 to 67.88. The reducing trend in h^* shows that the fruit is going through an advanced process of ripening that can be identified through increased yellowing as well as senescence-associated pigment conversion. As observed in other studies involving tropical fruits under extended period of storage, minor late-stage fluctuations could happen due to non-linear pigment degradation or physiological stress responses during senescence [53–56]. As a whole, h^* is a key metric of ripening progression although there's a variation in results of extended period of storage.

The mean values of main quality characteristics of *Terung Asam* over the 28-day storage period are illustrated in Table 1 in order to analyse the physicochemical variations. The characteristics are colour parameters (L^* , C^* , and h^*), fresh weight loss (FWL), firmness, soluble solid content (SSC), pH, as well as total chlorophyll content (TCC). Because of the relevance in characterizing the overall post-harvest quality together with ripening behaviour and senescence, these variables were selected to be used for subsequent kinetic modelling. Quality changes in deterioration during storage can be seen progressively as indicated by different superscript letters within the same column showing statistical significance in difference ($p < 0.05$).

3.1.2. Fruit firmness

A consistent and progressive decline was shown by the firmness of *Terung Asam* throughout the 28-day storage period, as depicted in Table 1. On Day 0, firmness averaged 5.52 N and dwindled progressively to 5.07 N on Day 7, 4.64 N on Day 14, 4.08 N on Day 21, and 3.34 N on Day 28. This progressive reduction shows typical postharvest softening linked to fruit ripening and senescence.

Enzymatic activities lead to fruit softening during storage whereby it degrades the components of cell wall like hemicellulose, pectin and cellulose [57,58]. Other fruits have also reported similar outcomes in experiments. Dautt-Castro et al [59] reported that, in mangoes, a sharp decrease in firmness was noticed during the upregulation of multiple polygalacturonase (PG) genes in postharvest ripening, that shows pattern solubilization is a main factor that drives softening. Similar outcomes were obtained in research involving papaya whereby a reduced firmness was observed during storage and this is mainly because of pattern solubilization and enzymatic degradation of cell wall polysaccharides, as recorded by Tao and Pan [60] and do Prado et al [61].

Furthermore, packing substances breakdown has a major role in this occurrence. Huang et al [62] found that the disruption of calcium–pectate cross-linking (egg-box structures) in loquat fruit contributes notably to reducing firmness during postharvest storage. The

Table 1

Mean physicochemical quality characteristics of *Terung Asam* during 28 days of ambient storage.

Storage Duration Days	Colour			FWL (%)	Firmness (N)	SSC (%)	pH	TCC (mg/100g)
	L^*	C^*	h^*					
0	52.97 ± 0.68 ^A	39.28 ± 2.0 ^A	97.29 ± 2.72 ^A	0.00 ± 0.00 ^A	5.52 ± 0.01 ^A	2.93 ± 0.05 ^A	4.51 ± 0.02 ^A	6.50 ± 0.02 ^A
7	56.73 ± 0.50 ^B	44.43 ± 0.56 ^B	80.05 ± 0.64 ^B	6.52 ± 0.22 ^B	5.07 ± 0.06 ^B	2.56 ± 0.07 ^B	4.58 ± 0.02 ^B	5.20 ± 0.05 ^B
14	56.02 ± 0.75 ^C	44.63 ± 0.38 ^C	70.96 ± 1.07 ^C	10.99 ± 0.55 ^C	4.64 ± 0.01 ^C	2.78 ± 0.07 ^C	4.49 ± 0.01 ^C	4.15 ± 0.05 ^C
21	49.02 ± 0.41 ^D	38.46 ± 0.99 ^D	66.64 ± 0.88 ^D	14.70 ± 0.59 ^D	4.08 ± 0.05 ^D	2.40 ± 0.04 ^D	4.41 ± 0.03 ^D	3.03 ± 0.04 ^D
28	48.28 ± 0.34 ^E	35.72 ± 0.19 ^E	67.88 ± 0.91 ^E	18.95 ± 0.77 ^E	3.34 ± 0.05 ^E	1.96 ± 0.03 ^E	4.48 ± 0.02 ^E	1.98 ± 0.07 ^E

Values are expressed as mean ± standard deviation ($n = 30$). Different superscript letters within the same column indicate significant differences at $p < 0.05$ based on LSD test.

middle lamella weakening and cell wall disassembly is facilitated by increasing peptin methylesterase (PME) activity and subsequently demethylesterification processes. Experiments with pears too have shown comparable patterns, as Zhang et al [63] found that the PbrPG6 gene plays a significant role in postharvest softening, with its expression is highly linked to both PG enzyme activity as well as reducing firmness. As a whole, these outcomes show that the decline in firmness of *Terung Asam* that happens progressively during storage could be due to similar biochemical mechanisms especially the enzymatic degradation that happens in pectin as well as the loss of cell wall stability that is mediated by calcium which are important signs of post-harvest softening in climacteric fruits. The structural significance of this firmness decline is further reinforced by the SEM and TEM observations presented in the following sections, which showed peel tissue collapse, cell wall loosening, and progressive ultrastructural deterioration during storage.

3.1.3. Fresh weight loss

As shown in Table 1, it is clear that the fresh weight of the fruit reduced in a progressive manner over the 28 days of storage period. From Day 0 to Day 28, a steady increase in the percentage of fresh weight loss (%FWL) can be observed. At Day 0, fresh weight loss was 0%, increasing to 10.99% by Day 14 and 14.70% by Day 21, before reaching the highest value of 18.95% on Day 28. The progressive increment shows a consistent trend in moisture loss which is typical to postharvest physiological change in fresh produce during the period of storage [64,65]. Transpiration and also respiration processes contribute largely to the reduction in weight and these leads to the loss of carbohydrates and water from the tissues of the fruit [66,67].

In experiments with eggplant fruits, a similar result had been obtained, whereby water loss during storage was primarily related to transpiration stress as well as respiration activity under ambient conditions that yield notable shrivelling and reduction in firmness [68,69]. Strong influence of conditions in the environment, especially humidity as well as temperature, on post-harvest moisture loss was depicted in an experiment by Kassebi and Korzenszky [70], found that apples that are being stored at ambient temperature of 25 degrees Celsius go through drastic weight losses over a period of three months' time ranging from 21.9 gram to 31.76 gram. These outcomes show the importance of humidity and temperature control in order to reduce the loss of water and also extend fruit's shelf life.

In addition, Gomes et al [64] found that it has been effective to vacuum-package in order to manage drastic loss of weight in murici fruits and this shows that enhanced packaging method could address similar losses in *Terung Asam* during extended period of storage. As water retention can be associated closely to the textural quality as well as visual quality of fruits, the increasing FWL in *Terung Asam* likely shows a reduction in marketability that happens concurrently because water loss that happens at an excessive rate contributes to shrivelling, reduction in firmness as well as reduced acceptability among consumers in numerous fruits during postharvest storage [71].

3.1.4. Soluble solid content

As shown in Table 1, there was a reducing pattern over the period of 28 days of storage in the soluble solid content (SSC) of *Terung Asam* fruits. In the beginning, SSC was at 2.93% and this figure had reduced to 2.56% by Day 7. However, it slightly increased to 2.78% on Day 14 but continued to reduce to 2.40% on Day 21 before reaching the lowest percentage of 1.96 on Day 28. This widely reducing pattern shows that an extended period of storage will lead to reduction in soluble solid which could be happening because of metabolic consumption of sugars through senescence-related enzymatic degradation of cellular components as well as respiration.

These outcomes are congruent with prior research on *Terung Asam* and other related Solanaceae fruits. For example, Rushdy et al [3] found a slow reduction in compounds that are related to antioxidants which include flavonoids as well as phenolics during 28-day storage research

on *Terung Asam* sauce, depicting biochemical degradation over time. Although the sample matrix differs from the fresh fruit examined in the present study, comparable degradation patterns may still occur, as both systems involve storage-related biochemical changes that affect quality-associated compounds over time. Tomatoes also show similar outcomes in research whereby SSC were affected by storage duration and conditions, with Brix values reducing or shifting in the period of extended storage [72].

The increasing trend at Day 14 could be due to the continued process of ripening that happened during early storage, where starches as well as other macromolecules got converted into simple sugars and enhancing the SSC. Nevertheless, after that, the fruit probably was subjected to senescence, which led to degradation of sugars and a reduction in SSC. In other Solanaceae fruits like *Solanum sessiliflorum* (cubiu), similar post-harvest physiological behaviour was observed, where SSC dropped drastically after an extended period of storage under ambient conditions [73]. In addition, Ibrahim et al [6] have underscored the antioxidant and biochemical sensitivity of *Solanum lasiocarpum* fruits, reinforcing that storage conditions largely affect phytochemical retention and nutritional quality.

3.1.5. Total chlorophyll content

As presented in Table 1, the total chlorophyll content of *Terung Asam* fruits showed a progressive and notable decline throughout the 28-day storage period. Initially, chlorophyll concentration was recorded at 6.50 mg/100g, which decreased steadily to 5.20 mg/100g by Day 7, 4.15 mg/100g on Day 14, 3.03 mg/100g by Day 21, and finally 1.98 mg/100g on Day 28. Chlorophyll degradation during postharvest storage, which leads to fruit senescence and ripening, has been clearly indicated by the consistent trend of reduction.

It has been documented in prior research that tissue aging as well as colour loss is related to chlorophyll breakdown, which happens in other fruits as well. For example, Wei et al [8] found that in apples, ethylene activates a ubiquitination pathway involving MdPUB24 and MdBEL7, encouraging the expression of chlorophyll catabolic genes, and enhancing chlorophyll degradation during storage. In the same light, Gorfer et al [74] noticed numerous chlorophyll degradation products (phylobilins) in apple peels when shelf life increased, suggesting that it can act as ripening markers.

The chlorophyll loss observed in *Terung Asam* may be due to the increasing activity of chlorophyll-degrading enzymes like chlorophyllase and pheophorbide an oxygenase, together with peroxidase systems, whereby all of them are stimulated by ethylene production and oxidative stress, as identified by Zhang et al [75] in 'Zaosu' pear and Kaewsuksaeng et al [54] in Thai lime. Noticeable yellowing or the degradation of green colour happens because these enzymes are converting chlorophylls into colourless catabolites.

In addition, oxygen availability and ambient temperatures among the host harvest environmental factors that could increase the rate of degradation. Research in limes, bananas and pests have identified that treatment with ethylene inhibitors like 1-MCP1-MCP or controlled atmosphere storage can dramatically slow down the breakdown of chlorophyll and increase nutritional as well as visual quality [76,77].

3.1. 6 pH level

The pH of *Terung Asam* fruit showed very little changes along the 28-day storage period as shown in Table 1. The pH recorded was 4.51 at Day 0 which increased a little bit to 4.58 by Day 7. On Day 14, the value reduced to 4.49 and on Day 21, it was the lowest recorded at 4.41 before it increased slightly to 4.48 on Day 28 (Table 1). Since only a slight difference was noticed throughout the experiment, it can be concluded that the fruit overall had a relatively stable acidity throughout the period of storage which goes to show that the inherent sourness of the fruit remained intact.

The pH reading from Day 7 to Day 21 reduced slightly and this could be due to the organic acid accumulation or reduced metabolic activity,

which is typical in ripening fruit. Nevertheless, the reading increased on Day 28 and this suggests that the concentration of organic acid radicals slightly which could be due to utilization of the acid during respiration or because of degradation process. This observation is in line with findings in other Solanaceae fruits. For example, a research on cubiu (*Solanum sessiliflorum* Dunal), which is closely linked to *Terung Asam*, identified that during the ripening process, the pulp pH and titratable acidity changed only slightly, although the placenta revealed greater changes in marked acidity [78].

Likewise, Rushdy et al [3] found that *Terung Asam* sauce formulations resulted in a very slight reduction in pH over the 28-day storage period, suggesting that the acidity of the fruit is considerably stable under typical conditions of storage. When it comes to product development, the stability noticed is advantageous because it increases the shelf-life predictability and control in fermentation in processed foods like juices and sauces. This also shows that the fruit could be stored for about a month with only small changes happening in acidity as this is crucial to preserve the taste and also ensure stability in microbial activities as well as the acceptability of consumers. Furthermore, it was found by Leona [79] that the pH values in *Terung Asam* juice remains stable for a few weeks when the fruit was stored before slight increases in the pH was noticed, and this finding is aligning with previous studies that show that acidity does not drop dramatically during short-term storage.

3.2. Correlation analysis of quality parameters

The Pearson correlation analysis showed strong as well as significant relationships ($p < 0.01$) among most physicochemical parameters of *Terung Asam* during storage as depicted in Table 2. L^* and C^* which showed a strong positive correlation at $r = 0.896$, indicating that the reduction in lightness happened alongside with reduction in colour intensity, suggesting that chlorophyll degradation happened when the duration of storage increased. Research with papaya and mango also yielded similar results, where reductions in L^* and C^* values were in agreement with the loss of chlorophyll pigments as well as the transition from green to yellowish colour during ripening [80,81].

h^* value was positively correlated with firmness at $r = 0.837$ and TCC at $r = 0.905$, but strongly negatively correlated with FWL at $r = -0.927$, showing that when there is an increase in moisture loss, the rate of fruit softening increased, and the degradation of chlorophyll increased as well. The positively associated h^* and TCC shows that when the chlorophyll content is more, it helps to retain the greener colour and slow down the transition of colour change. Similar link between h^* values, firmness, and TCC retention found in findings related to stored fruits like *Zaosu* pear and mango, where chlorophyll loss that happens progressively corresponded with softening and decreasing h^* values when the fruit is being storage [82,83].

Firmness suggested a highly negative correlation with FWL at $r = -0.974$ and a strong positive correlation with TCC at $r = 0.988$ showing that tissue softening happens alongside chlorophyll degradation as well as increased water loss. Similar findings were reported in experiments involving *Annona* species and guava, where it was found that loosening

of the cell wall as well as softening of the fruit during ripening happened when chlorophyll content drops [84,85].

A strong negative correlation between FWL and SSC at $r = -0.853$ showed that when water loss happened dramatically, the consideration of sugar inclined to reduce, and this is attributed to reduced carbohydrate metabolism or the effects of dilution. Contrastingly, firmness correlated positively with SSC at $r = 0.907$, and this shows that accumulation of sugar in a moderate level showed a positive impact on osmotic balance as well as delaying the softening process, and this was observed in experiments involving melon and passion fruit during controlled postharvest storage [86,87].

The positive correlation between pH and SSC at $r = 0.297$ was moderate, showing that the reduced acidity happened along with increasing concentration of sugar during the ripening process. This change in metabolism shows that organic acids were converted into sugar, which is a typical observation in climacteric fruits like soursop [88]. The correlation analysis showed that firmness, FWL, and TCC are the most interdependent parameters influencing quality changes after harvest in *Terung Asam*. The strong interrelationships between these variables show that they play a role as dependable indicators for predicting fruit senescence kinetics and modelling storage stability.

3.3. Microstructural image

Scanning electron microscopy (SEM) of *Terung Asam* peel at 2000 $\times$ magnification showed clear morphological changes in stomatal structures throughout the 28-day storage period, as shown in Fig. 2. At Day 7, the stomata measured approximately 9.98 $\mu\text{m} \times 14.18 \mu\text{m}$ (Fig. 2A) and appeared relatively intact, with well-defined guard cells and moderately open pores. This morphology suggests that gas exchange was still active and that the peel tissue retained sufficient hydration during the early stage of storage. This observation was consistent with the relatively low FWL value of 6.52% at Day 7, as shown in Table 1.

By Day 14, the stomatal structure increased in size to approximately 13.71 $\mu\text{m} \times 19.71 \mu\text{m}$, as shown in Fig. 2B. Although the measured stomatal dimensions increased, the pore opening appeared slightly constricted and less regular, suggesting an early adaptive response to increasing moisture loss and reduced turgor pressure. This corresponded with the increase in FWL to 10.99% by Day 14 (Table 1). Similar stomatal responses have been reported in climacteric fruits such as papaya and mango, where dehydration during storage affected pore structure and epidermal water balance [89,90]. Similar observations were also reported in blueberries, where wax deposition within the stomatal cavity reduced water permeability and limited desiccation during storage [91]. These early microstructural changes in *Terung Asam* may therefore reflect a short-term adaptive mechanism to regulate epidermal water balance while maintaining respiration-driven gas exchange. Stomatal regulation controls water vapour loss and the diffusion of oxygen (O_2) and carbon dioxide (CO_2) in plant tissues, directly influencing transpiration and respiration rates [92].

As storage progressed, more distinct stomatal deformation was observed at Day 21 and Day 28. Fig. 2C and 2D show collapsed and irregular guard cells, together with partially or fully occluded apertures.

Table 2

Pearson correlation coefficients among physicochemical quality parameters of *Terung Asam* during ambient storage.

	L^*	C^*	h^*	Firmness	FWL	SSC	TCC	pH
L^*	1							
C^*	0.896**	1						
h^*	0.377**	0.132	1					
Firmness	0.724**	0.573**	0.837**	1				
FWL	-0.607**	-0.417**	-0.927**	-0.974**	1			
SSC	0.677**	0.588**	0.677**	0.907**	-0.853**	1		
TCC	0.666**	0.481**	0.905**	0.988**	-0.994**	0.872**	1	
pH	0.714**	0.539**	0.487**	0.541**	-0.523**	0.297**	0.560**	1

Values represent Pearson correlation coefficients (r). ** indicates correlation is significant at $p < 0.01$.

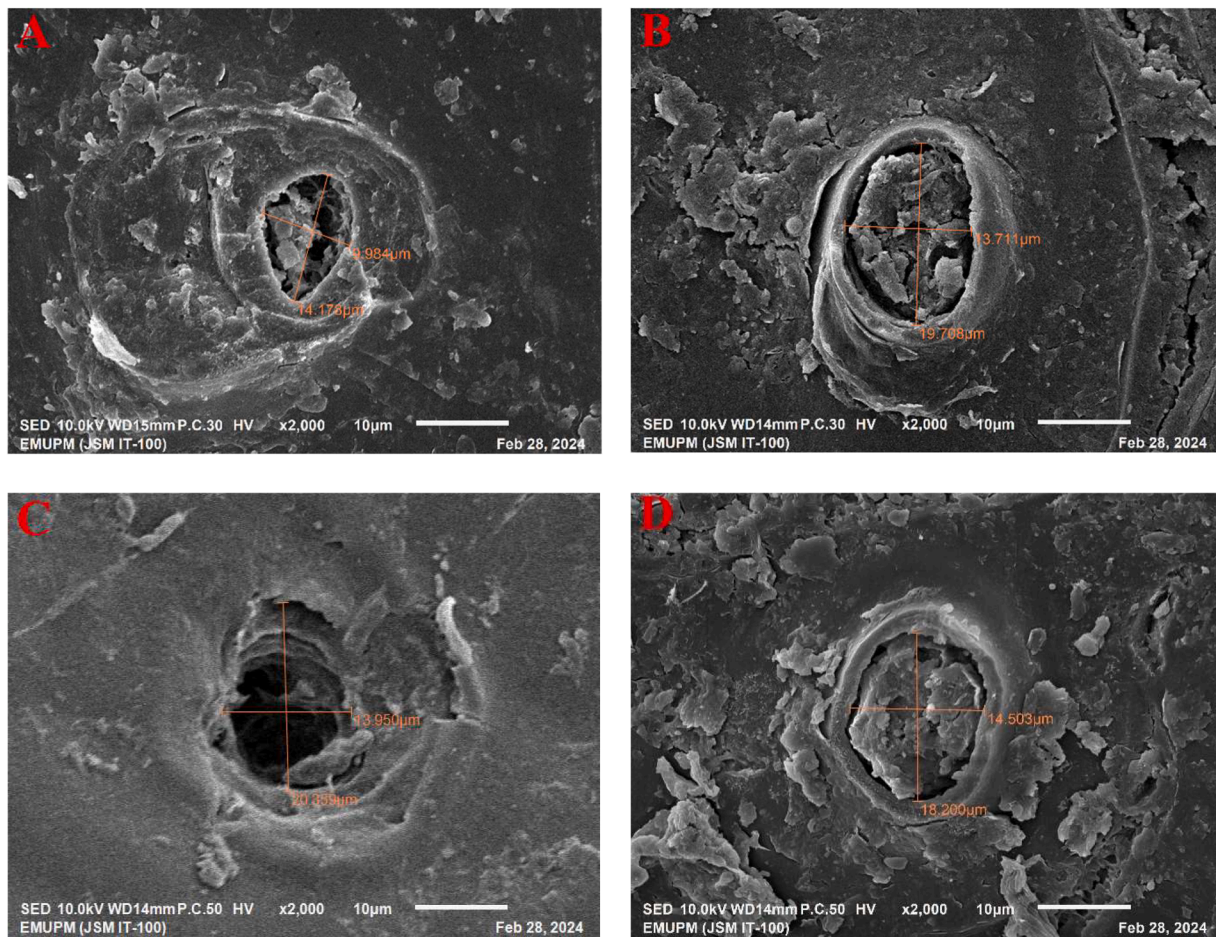


Fig. 2. Scanning electron micrographs (2000x) of Terung Asam peel showing stomatal morphology across the 28-day storage period: (A) Day 7, (B) Day 14, (C) Day 21 and (D) Day 28.

The stomatal structures measured approximately $12.95 \mu\text{m} \times 17.21 \mu\text{m}$ on Day 21 and $14.50 \mu\text{m} \times 18.20 \mu\text{m}$ on Day 28. These structural changes coincided with the continued increase in FWL from 14.70% on Day 21 to 18.95% on Day 28 (Table 1), indicating that prolonged ambient storage intensified moisture loss and surface deterioration. The occlusion and deformation may have resulted from dehydration-induced cell collapse, phenolic residue accumulation, or surface wax reorganisation, reflecting irreversible senescence and loss of stomatal functionality. Similar outcomes have been reported in climacteric fruits such as soursop and kiwifruit, where prolonged storage caused pore deformation, cuticle breakdown, and reduced gas exchange capacity [93,94].

Furthermore, metabolomic analyses of climacteric fruit tissues have shown that increasing internal ethylene (C_2H_4) and CO_2 concentrations during storage can affect respiratory metabolism and contribute to stomatal closure [95–97]. Ethylene is a major ripening hormone that accelerates senescence by enhancing respiration and altering gas diffusion pathways [98]. Therefore, the progressive transition from relatively open and functional stomata during early storage to collapsed or occluded pores during later storage suggests increasing senescence-related surface deterioration. This structural change may have reduced normal gas exchange and contributed to surface shrivelling, moisture loss, and overall quality decline in *Terung Asam* during ambient storage.

3.4. Ultrastructural image

Transmission electron microscopy (TEM) showed progressive ultrastructural changes in the peel cells of *Terung Asam* during 28 days of

storage, as shown in Fig. 3. During the early storage stage at Day 7, the cellular architecture was relatively well organised, with continuous cell walls and intact mitochondria and chloroplasts as shown in Fig. 3A. The chloroplasts showed compact and well-stacked thylakoid membranes [99], while the mitochondria exhibited clearly defined cristae, suggesting active respiratory function [100]. These observations were consistent with the relatively high firmness recorded during early storage, where firmness decreased from 5.52 N at Day 0 to 5.07 N at Day 7, while TCC declined from 6.50 mg/100 g to 5.20 mg/100 g, as shown in Table 1.

By Day 14, early senescence-related changes became more evident as shown in Fig. 3B. The chloroplasts showed partial disorganisation and thylakoid swelling, while the mitochondria exhibited vacuolisation, cristae thinning, and occasional detachment of the outer membrane. These changes suggest the onset of respiratory disruption and oxidative stress. At the same time, the occurrence of intercellular separation and cell-wall loosening indicated the beginning of pectic degradation, which corresponded with the continued decline in firmness to 4.64 N and TCC to 4.15 mg/100 g (Table 1). Similar structural weakening has also been observed in other climacteric fruits such as citrus and kiwifruit [101, 102]. Comparable ultrastructural transitions have been identified in *Actinidia deliciosa* and ‘Cuixiang’ kiwifruit, where prolonged storage resulted in membrane disintegration, cell-wall relaxation, and enzymatic softening [42,103].

At Day 21 and Day 28, severe ultrastructural deterioration was observed, as depicted in Fig. 3C and 3D. The chloroplasts showed loss of internal membrane organisation, while the mitochondria appeared swollen and ruptured. The cell walls also became thinner and more

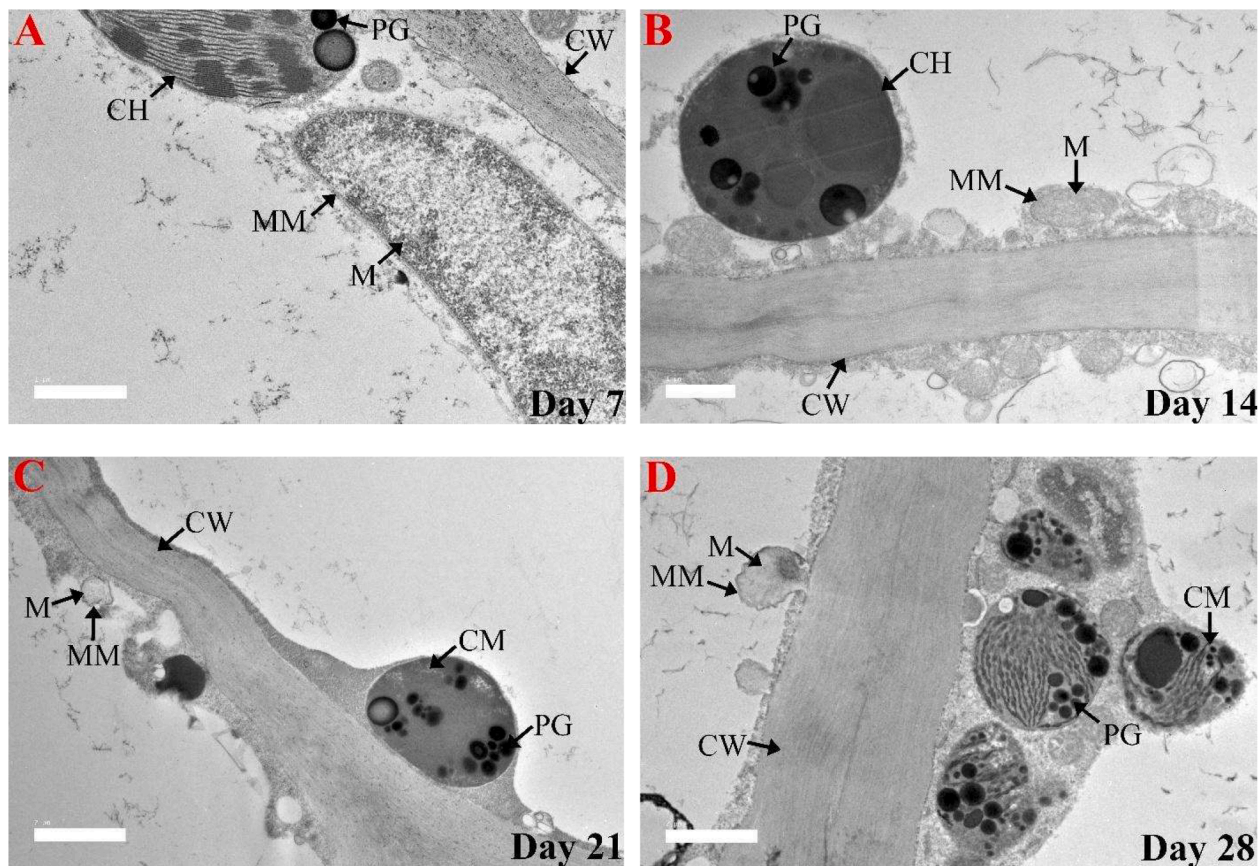


Fig. 3. Ultrastructural images of Terung Asam peel across the storage duration obtained using transmission electron microscopy (TEM). (A) Day 7, (B) Day 14, (C) Day 21 and (D) Day 28. Mitochondria: M, Mitochondria Membrane: MM, Cell Wall: CW, Chloroplast: CH, Chromoplast: CM, and Plastoglobules: PG.

irregular, with larger intercellular spaces. These changes corresponded with the marked decline in firmness from 4.08 N at Day 21 to 3.34 N at Day 28, as well as the reduction in TCC from 3.03 mg/100 g to 1.98 mg/100 g, as shown in Table 1. This indicates that advanced softening and pigment degradation occurred alongside cellular and subcellular breakdown. Such trends are consistent with reports linking fruit softening to cell-wall remodelling and reduced mechanical strength through enzymatic hydrolysis of pectin, hemicellulose, and cellulose [104]. The loss of chloroplast and mitochondrial integrity also reflects accelerated senescence and quality deterioration, as reported in other climacteric fruits [105,106].

Prolonged storage also resulted in mitochondrial membrane rupture, cristae disintegration, and mitochondrial swelling in *Terung Asam* peel cells. These changes suggest reduced mitochondrial function, possible ATP depletion, and disrupted respiration, which may limit the energy available for maintaining membrane integrity and cell-wall stability. Similar declines in mitochondrial function and energy metabolism have been reported in stored tomato, citrus, and kiwifruit, where reduced respiratory enzyme activity, lower ATP synthesis, and redox imbalance were closely associated with firmness loss and tissue softening [107–109]. Mitochondrial dysfunction may also increase reactive oxygen species (ROS) accumulation, further accelerating membrane damage, cell-wall weakening, and senescence.

The reduction in TCC from 6.50 mg/100 g at Day 0 to 1.98 mg/100 g at Day 28, as depicted in Table 1 was consistent with the observed transition from organised chloroplasts to degraded plastids. This was indicated by thylakoid disassembly, plastoglobule accumulation, and the appearance of chromoplast-like structures [110–112]. The TEM images showed that plastoglobules became more visible as storage progressed, suggesting increased lipid and carotenoid accumulation during chloroplast-to-chromoplast transition. Since plastoglobules are

lipid-rich compartments associated with carotenoid storage, their increased presence supports the visible colour shift from green to yellow-orange during storage. Overall, the concurrent decline in firmness from 5.52 N to 3.34 N and TCC from 6.50 mg/100 g to 1.98 mg/100 g (Table 1) suggests that tissue softening and pigment degradation were accompanied by mitochondrial deterioration, plastid degradation, and cell-wall disassembly in *Terung Asam* during storage.

Although the TEM observations provided structural support for the observed kinetic trends, their relationship with the kinetic parameters was interpreted qualitatively. The microscopy analysis was used to characterise representative ultrastructural deterioration during storage, including chloroplast disorganisation, thylakoid disruption, mitochondrial damage, and cell-wall loosening. Therefore, the observed relationship between ultrastructural degradation and changes in TCC or firmness provides mechanistic support for the physicochemical deterioration pattern, but does not represent a direct quantitative correlation with the reaction rate constant (k).

3.5. Kinetics of quality changes in *Terung Asam* during storage

In this research, both zero-order and first-order kinetic models were applied to main physicochemical parameters of *Terung Asam* which are L^* , C^* , h^* , firmness, FWL, SSC, TCC, and pH over a storage period of 28 days as depicted in Table 3. In the present study, the kinetic order was used to represent the apparent deterioration behaviour of the whole fruit during storage. This is because postharvest quality attributes such as firmness, colour, FWL, SSC, TCC, and pH are not governed by a single reaction pathway, but reflect the combined effects of several biochemical and physical processes occurring simultaneously. Accordingly, model selection was guided by R^2 , RMSE, the observed storage trend, and the biological relevance of the deterioration mechanism.

Table 3

Kinetic parameters and model performance statistics for physicochemical quality changes in *Terung Asam* during ambient storage.

Parameter	Zero-Order Model			First-Order Model		
	K	R ²	RMSE	k (day ⁻¹)	R ²	RMSE
L*	0.2441	0.497	2.499	0.0047	0.499	2.536
C*	0.1869	0.280	2.964	0.0048	0.299	3.000
h*	1.0321	0.806	5.008	0.0129	0.829	4.519
Firmness	0.0765	0.986	0.089	0.0175	0.964	0.144
FWL	0.6583	0.988	0.731	0.3588	0.574	0.844
SSC	0.0300	0.781	0.157	0.0124	0.771	0.167
TCC	0.1602	0.998	0.062	0.0417	0.979	0.247
pH	0.0033	0.377	0.043	0.0007	0.377	0.043

For zero-order models, k is expressed in the unit of each quality parameter per day, while for first-order models, k is expressed as day⁻¹. RMSE values are expressed in the original units of each parameter and should be compared only between zero-order and first-order models within the same parameter. For first-order modelling of FWL, Day 0 was excluded because $\ln(0)$ is undefined.

The L^* and C^* parameters showed weak model fit under both kinetic models. For L^* , the first-order model produced a slightly higher R^2 value of 0.499 compared with 0.497 for the zero-order model. However, the zero-order model showed a slightly lower RMSE of 2.499 compared with 2.536 for the first-order model. Similarly, C^* showed low R^2 values under both zero-order and first-order models, with RMSE values of 2.964 and 3.000, respectively. These results indicate that L^* and C^* did not follow a strong zero- or first-order kinetic pattern during ambient storage. This may be attributed to the combined influence of several postharvest processes affecting lightness and chroma simultaneously. In climacteric fruits such as mango and banana, changes in L^* , C^* , and h^* during storage have been associated with ripening-related pigment transformation, chlorophyll degradation, carotenoid accumulation, respiration, ethylene activity, oxidative stress, browning, and senescence-related surface deterioration [113–116]. In addition, enzymatic browning is driven by the oxidation of phenolic substrates by oxidative enzymes such as PPO and POD, leading to quinone formation and brown pigment accumulation, while moisture loss and respiration can further accelerate visual dullness and quality deterioration during storage [117,118]. Similar non-linear colour behaviour has been identified in postharvest apples and pineapples, where concurrent enzymatic and oxidative reactions complicated kinetic fitting [20,119]. Therefore, L^* and C^* were retained as descriptive colour indicators but were interpreted with caution as kinetic predictors.

In contrast, h^* showed better kinetic conformity and was more appropriately described by the first-order model. The first-order model produced a higher R^2 value of 0.829 and a lower RMSE of 4.519 compared with the zero-order model, which recorded an R^2 value of 0.806 and RMSE of 5.008. This suggests that the hue shift during storage was more dependent on the remaining pigment intensity than on a constant rate of change. As *Terung Asam* ripened and senesced, the progressive reduction in h^* reflected a colour transition from green or yellow-green tones towards yellowing, which is commonly associated with chlorophyll degradation and the increasing visual dominance of yellow-orange pigments. This interpretation is supported by studies on climacteric fruit such as mango, where postharvest yellowing and declining hue angle were linked to chlorophyll degradation, carotenoid accumulation, ethylene-related ripening, and peel colour transformation [120–122]. A similar green-to-yellow transition has also been reported during ripening of naranjilla or lulo (*Solanum quitoense*), a related *Solanum* fruit, where colour change was associated with chlorophyll degradation [123]. Therefore, h^* was considered a more reliable colour-based kinetic indicator than L^* and C^* under the tested ambient storage conditions.

Firmness reduced progressively as storage duration increased and was better described by the zero-order model, with $R^2 = 0.986$, $k =$

0.0765, and RMSE = 0.089, compared with the first-order model, which recorded $R^2 = 0.964$, $k = 0.0175$ day⁻¹, and RMSE = 0.144. This indicates that the measured whole-fruit firmness declined at an approximately constant rate during ambient storage. However, this zero-order behaviour should not be interpreted as evidence that the individual enzymatic reactions responsible for cell-wall degradation followed zero-order kinetics. Fruit softening is a complex whole-tissue response involving coordinated biochemical and physical changes. Recent studies have shown that postharvest softening is closely associated with pectin and hemicellulose modification, increased pectin-degradation enzyme activity, and upregulation of cell-wall disassembly genes such as PG, PME, PL, and β -Gal/GAL [58,124]. In addition, overexpression of the raspberry polygalacturonase gene *RIPG2* in tomato reduced fruit firmness, increased PG activity, and altered cell-wall components, including water-soluble pectin, ion-bound pectin, protopectin, cellulose, and hemicellulose [125]. Therefore, the apparent zero-order firmness loss observed in *Terung Asam* likely reflects the net macroscopic effect of multiple overlapping processes, including enzymatic pectin degradation, pectic solubilisation, middle lamella weakening, hemicellulose and cellulose remodelling, calcium-pectate disruption, moisture loss, turgor reduction, and progressive structural weakening of fruit tissues [42,112,126]. A comparable zero-order decline in firmness has also been reported in tomatoes under ambient storage, suggesting that the combined effects of mechanical degradation, water loss, and whole-tissue structural weakening may produce an approximately linear firmness decline, even though the underlying enzyme-mediated reactions may be substrate dependent [21].

FWL was best described by the zero-order model, with $R^2 = 0.988$ and RMSE = 0.731 compared with $R^2 = 0.574$ and RMSE = 0.844 for the first-order model. This suggests that fresh weight loss increased at an approximately constant rate under the tested ambient conditions. Mechanistically, the apparent zero-order behaviour of FWL is more directly linked to physical water movement than to concentration-dependent biochemical reactions. Postharvest water loss is mainly governed by transpiration, diffusion, and moisture transfer across the fruit surface, particularly through the peel, cuticle, and stomatal pathways. Recent reviews have emphasised that water loss during storage directly affects fruit quality, shelf life, market value, firmness, and visual appearance [65,127]. Fruit transpiration can also occur through both cuticular and stomatal pathways, as shown in banana fruit, where both routes contributed substantially to postharvest water loss [128]. Therefore, the zero-order FWL pattern observed in *Terung Asam* is biologically plausible because the fruits were stored under relatively constant ambient temperature and relative humidity, allowing moisture migration and transpiration to proceed steadily over time. This interpretation agrees with recent findings that fruit water loss during storage is primarily controlled by physical transport mechanisms such as transpiration and diffusion, which can result in near-linear fresh-weight loss patterns [127,129,130]. Similar linear weight-loss patterns have also been reported in papaya and lime stored under ambient conditions [49,131]. Thus, unlike firmness loss, which involves both enzymatic cell-wall degradation and physical tissue weakening, the zero-order behaviour of FWL can be more directly attributed to steady physical moisture loss during ambient storage.

SSC showed moderate but not strong kinetic performance under both models. The zero-order model showed a slightly higher R^2 value and lower RMSE than the first-order model, with $R^2 = 0.781$ and RMSE = 0.157 compared with $R^2 = 0.771$ and RMSE = 0.167. Although this suggests a slightly better zero-order fit, the relatively close performance of both models indicates that SSC changes were not governed by a single dominant kinetic process. Instead, SSC variation during storage may reflect the simultaneous occurrence of starch hydrolysis, sugar accumulation, sugar interconversion, and respiratory sugar utilisation. Such metabolic interplay has been reported in postharvest fruit systems, where starch degradation and sugar consumption occur concurrently and lead to variable SSC patterns during storage [132,133]. Similar

mixed kinetic outcomes have been reported in mango and cucumber fruits, where SSC changes were influenced by concurrent starch breakdown and sugar conversion processes [134,135], while SSC increases during storage have also been observed in tropical fruits such as mulberry [136]. Therefore, SSC was interpreted as a supporting quality parameter and not a primary kinetic indicator.

TCC declined progressively during storage and was best described by the zero-order model, with $R^2 = 0.998$ and $RMSE = 0.062$, compared with the first-order model, which recorded $R^2 = 0.979$ and $RMSE = 0.247$. This indicates that the measured chlorophyll content decreased at an approximately constant rate during ambient storage. Therefore, the zero-order behaviour of TCC reflects the overall tissue-level pattern of chlorophyll loss during storage. This does not necessarily indicate that each individual chlorophyll-degradation reaction followed the same kinetic order. Mechanistically, chlorophyll degradation during ripening and senescence involves coordinated pigment-catabolic processes, including chlorophyllase, magnesium dechelatase, peroxidase activity, and the PAO-phytylkinase pathway, which convert chlorophyll into pheophytin and other colourless or non-green catabolites, leading to visible greening and yellowing of the peel as storage progresses [137, 138]. Recent studies on pear and kiwifruit have also shown that post-harvest greening is associated with changes in chlorophyll-degradation enzymes, oxidative stress, and related gene expression [82,139]. In climacteric fruits, ethylene can further regulate colour development and chlorophyll degradation during ripening and senescence [98]. Similar enzyme-driven chlorophyll degradation has been observed in broccoli and 'Golden Ball' apples, where enhanced peroxidase and chlorophyllase activities increased pigment loss [140, 141]. Therefore, the zero-order TCC decline observed in *Terung Asam* is best interpreted as the net macroscopic outcome of continuous chlorophyll breakdown at the peel tissue level, supported qualitatively by the TEM observations showing chloroplast disorganisation and degradation during storage. These findings support the interpretation that pigment degradation occurred during storage. However, the present study did not directly measure chlorophyll-degrading enzyme activities or related gene expression. Therefore, the zero-order TCC model represents a quantitative description of the steady overall decline in chlorophyll content in *Terung Asam* during ambient storage, without confirming the molecular kinetic behaviour of individual chlorophyll-catabolic reactions.

The pH values of *Terung Asam* showed weak fits under both zero- and first-order models, with both models recording $R^2 = 0.377$ and nearly identical RMSE values of 0.043. This indicates that pH did not follow a clear zero- or first-order kinetic pattern under the tested ambient storage conditions. The low R^2 values, together with the minimal difference in RMSE between the two models, suggest that neither model adequately described the pH changes during storage. The irregular pH fluctuations may reflect competing processes, including organic acid consumption through respiration, possible microbial activity, and enzymatic de-esterification of pectin, which can produce non-linear shifts in acidity. Similar pH fluctuations have been observed in red raspberry and zucchini, where metabolic and microbial activity caused inconsistent acid trends rather than predictable decay [142,143]. Broader metabolomic studies also show that organic acid pools in fruits can change dynamically under respiration and stress responses [132], while kinetic modelling in cayenne pepper and cherry tomatoes has shown that pH trajectories may vary depending on storage conditions and physiological stage [129,144]. Therefore, pH was not considered a reliable kinetic parameter for predicting *Terung Asam* quality deterioration under the tested conditions and should be interpreted with caution. In the present study, pH was retained as a supporting physicochemical indicator of acidity stability, not as a primary kinetic indicator of shelf-life deterioration.

Overall, the kinetic modelling results showed that the suitability of zero- and first-order models varied according to the physicochemical parameter evaluated. Firmness, FWL, and TCC were best described by

apparent zero-order kinetics, reflecting near-linear whole-fruit deterioration associated with tissue softening, steady moisture loss, and progressive chlorophyll degradation, respectively. In contrast, h^* was better described by first-order kinetics, indicating that the hue shift was more dependent on the remaining pigment intensity during ripening and senescence. Parameters such as L^* , C^* , SSC, and pH showed weaker or less consistent kinetic behaviour and were therefore interpreted with caution. These findings indicate that the kinetic models describe the overall deterioration pattern of the whole fruit and should be interpreted together with the biochemical and physical changes involved in post-harvest quality loss.

4. Conclusion

As a conclusion, this research presents a kinetic model describing the changes in quality of *Terung Asam* during 28 days of ambient storage. The statistical analysis revealed significant differences ($p < 0.05$) among all quality parameters across different storage times, while correlation analysis revealed strong interrelationships ($p < 0.01$) among firmness, FWL, and TCC, identifying them as main indicators of postharvest deterioration. The quality changes in firmness, FWL, and TCC were satisfactorily described by the zero-order kinetic model, whereas h^* followed first-order kinetics, indicating progressive moisture loss, tissue softening, and pigment degradation during storage. Microstructural and ultrastructural observations supported these kinetic trends, showing progressive stomatal deformation, chloroplast disintegration, and mitochondrial collapse linked with senescence. The 28-day ambient storage period was selected to capture the full progression of quality deterioration under room-temperature conditions, allowing kinetic modelling of changes from early ripening to advanced senescence. Since this study was conducted only under ambient conditions at $25 \pm 2^\circ\text{C}$ and 65–75% relative humidity, the developed models should be interpreted within the tested storage range. Future studies should validate the models under refrigerated and fluctuating temperature conditions, and include semi-quantitative ultrastructural analysis to strengthen the relationship between structural degradation and kinetic parameters.

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CRediT authorship contribution statement

Sophia Ann Suring: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation. **Bernard Maringgal:** Writing – review & editing, Validation, Supervision, Software, Project administration, Funding acquisition, Conceptualization. **Norhashila Hashim:** Writing – review & editing, Software. **Nurazwin Zulkifli:** Writing – review & editing, Software, Formal analysis.

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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Data availability

All data generated or analysed in this research are presented within this published article.

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