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Fractal image analysis and bruise damage evaluation of impact damage in guava

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ABSTRACT

Impact bruise damage and quality of 'Gim Ju' guava were investigated for different drop heights and number of drops using fractal image analysis. For the impact test, a stainless-steel metal ball (250 g) was dropped on fruit from three drop heights (0, 0.3, 0.6 m) either once or five times. Fruit quality was evaluated for impact energy, bruise area (BA), bruise volume (BV), bruise susceptibility, bruise score and pulp color (L^*, a^*, b^* and C values). The fractal dimension (FD) value using fractal image analysis was analyzed at the bruise region. Results showed that five drops (0.3 m) with a high impact energy (3 678.75 J) and a single drop (0.6 m) with a low impact energy (1 471.50 J) exhibited no significant in BA, BV, bruise score as well as all color values (L^*, a^*, b^* and C). While the FD value of a single drop from 0.6 m had a higher FD value than that of five drops from 0.3 m. It is indicated that FD exhibited a better performance to classify impact bruising level of guava than BA, BV and color parameters. The FD value gradually decreased with increase of storage time and bruise severity. The correlation coefficient (r) values of FD (r = − 0.794 and − 0.745) between BA and BV were more significant than those L^* (r = − 0.660 and − 0.615) and a^* (r = 0.579 and 0.473). The coefficient of determination (R^2) of the polynomial equation in bruised fruit (R^2 = 0.85 to 0.99) was greater than the control (no bruise) (R^2 = 0.80). A higher R^2_{val} (0.88 and 0.92) was exhibited at five drops. Interestingly, FD analysis showed greater potential than color measurement to assess bruise impact damage in guava.

1. Introduction

Guava (*Psidium guajava* L.) is an important commercial fruit in Thailand. The country is ranked sixth in global guava production [1]. Recently, export of guava from Thailand decreased gradually from 9 to 5.6 million tons from 2019 to 2021 [2]. Most guava fruits are susceptible to different types of damage during harvesting, handling and transportation, resulted in

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bruising and a postharvest loss of the quality [3]. The main issue affecting the marketing of Thai guava is its high perishability. The fruit ripens quickly due to loss of moisture with browning of the flesh, softening and fungal decay [1].

Fruit impact damage is more serious than vibration and compression damages. Impact damage occurs when the fruit drops with adequate force onto a surface, while dynamic damage of single fruit occurs in fruit-to-fruit impact and between packaging. Impact damage usually happens in free drops of fruit from trees to the ground during harvesting, from dynamic impact between single fruit and between the fruit and packaging or containers [4]. Various factors affect impact bruise damage testing such as drop height, number of drops, impact surface and packaging [5]. Previously, drop height and number of drop factors were reported in impact bruise susceptibility studies for various fruit such as apple [6], pomegranate [7], peach [8], and strawberry [9]. However, no report has studied impact bruise damage of guava fruit for different drop heights and number of drops.

General bruise assessments were determined by the parameters bruise area (BA), bruise value (BV), bruise susceptibility (BS), specific bruise susceptibility (SBS) and bruise score. The BS of impact bruising was determined by the ratio of bruise volume (BV) to impact energy [10–12]. For example, BA and BV were exhibited in fruit damaged apple [7,13], pomegranate [7] and peach [13]. BV increased linearly with increasing drop height and mass of apple [5] and pomegranate [14]. BS of impact bruising in pear highly related to CIE L^*, a^*, and b^* color coordinates with a strong linear regression under different drop height levels and storage conditions [15]. In tomato, there was a significant correlation of storage duration, storage temperature, and drop height with BA and a* *(R^2 value of 0.76 to 0.95) [16]. Until recently, most general assessments have been applied in impact bruise assessment of fruit [15,16]. Image analysis is a beneficial and useful automatic tool for non-destructive fruit quality evaluation. It is rapid, effective, low cost and more consistent than human evaluation that suffers from fatigue and lack of attention [17]. Image features, i.e., color, size, shape and texture can be used to assess fruit qualities [18]. Generally, color features can be used to evaluated fruit mechanical, physical and chemical properties such as ripening, index of maturity and fruit defects [17]. Several studies have been conducted to determine quality assessment and significant color changes in different fruit such as apple [19], pineapple [20], orange [21] and mango [22]. Bruise damage was analyzed using ImageJ software, including image pre-processing, region of interest (ROI) segmentation and features extraction. Previous studies conducted fruit quality evaluation using image textural feature, e.g. fractal dimension (FD) analysis to estimate fruit internal browning, color change in flesh and fruit defects such as banana [23], pear and apple [24] and pineapple [25,26]. Avocado fruit browning was also assessed using fruit images during storage and FD analysis was proved to be an accurate browning evaluator. FD values successfully described the occurrence of enzymatic browning in fresh produce [25]. Recently, the first study of FD exhibited a better indicator than bruise area or bruise volume measurement for pulp browning and impact bruising damage of 'Glom Sali' guava [27]. In addition, normalized FD difference ($\Delta FD/FD_0$) exhibited greater reliability and repeatability than BA from image analysis to determine vibration bruising of 'Glom Sali' guava under simulated transportation [28]. Therefore, FD analysis is an essential tool that can be used to determine postharvest flesh appearance [29].

Several studies employed image analysis to assess impact bruising on apple using different techniques such as hyperspectral imaging [30–32], thermal imaging [33] and X-ray computed tomography [34]. In guava, vis-NIR imaging was used to determine impact bruising [35]. Previous techniques for image analysis of impact bruising required advanced instruments and complex data interpretation procedures, while to the best of our knowledge. Recently, only one study has assessed impact bruising damage of guava using simple fractal image analysis. Three main factors for impact testing were investigated in drop height, a number of drops, storage temperature by using response surface methodology (RSM) on quality of 'Glom Sali' guava after storage for 2 days [27]. Also, a period of storage time may affect a changes of FD value after impact testing. There has been little fractal image analysis of impact bruising of fruits under different simulated impact conditions. Therefore, the aim of this study was to investigate the impact bruising damage of 'Gim Ju' guava under different drop heights and number of drops using fractal image analysis throughout storage time.

2. Materials and methods

2.1. Sample preparation

The 'Gim Ju' guava fruit was randomly collected from 'Poncharoen' orchard (latitude 20° 18′ 01.5″N and longitude 100° 01′ 04.9″E) Pa-sak village, Chiang Sean District, Chiang Rai Province, Thailand. Guava fruit were harvested in the morning, safely packed with foam net and polythene bags and transported to the laboratory S7 building at Mae Fah Luang University within 3 h. The random 'Gim Ju' guava fruits (15 fruits) were selected and examined for fruit properties by checking uniformity, guava maturity, fruit weight, volume, density, diameter, firmness, total soluble solids (TSS) and dry matter. Average weight of guava and density fruit were 250.29 g and 0.73 g/mL respectively (Table 1). Fruit density at<1.0 g/mL indicates top quality at the mature stage for harvesting and optimal consumer acceptability [3]. The fruits were selected for uniformity of size as horizontal width 7.76 cm and vertical length 8.03 cm as shown in Table 1. All samples were free from defects, diseases and mechanical damages.

2.2. Bruise susceptibility testing of guava fruit

A simulated impact test was set up using a pipe with a diameter of 9 cm adapted from Hussein [14] for impact testing of pomegranate. Each fruit was placed over a shallow depression (a diameter of 8 cm) in the foam sheet material with dimensions 20 × 23 × 2 cm, as shown in Fig. 1. A stainless-steel ball (diameter 8 cm and weight 250 g) with similar size and weight of a guava fruit was dropped on each guava fruit from different heights and number of times. A completely randomized design (CRD) with five treatments was used with five repli-

Table 1 – Fruit characteristics of 'Gim Ju' guava subjected to simulated impact testing.

Fruit characteristics	Mean ± S.E.
Fruit weight (g)	250.29 ± 6.79
Volume (mL)	322.0 ± 7.53
Density (g/mL)	0.73 ± 0.02
Horizontal diameter (cm)	7.76 ± 0.10
Vertical length (cm)	8.03 ± 0.11
Firmness (N)	6.12 ± 0.20
Total soluble solids (TSS) (%)	6.83 ± 0.11
Dry matter (%)	9.22 ± 0.20

Results of fifteen random fruit samples before impact testing (n = 15).

cates per treatment. The five treatments involved different drop heights and number of drops as: 1) no drop (control), 2) height of 0.3 m for one drop, 3) height of 0.3 m for five drops, 4) height of 0.6 m for one drop and 5) height of 0.6 m for five drops. Five drops were assumed as the probable number during postharvest handling of guava throughout the supply chain [3]. Impact energy (E) from the drop impact was calculated by $E = mgh$, where m is the guava mass, g is the gravitational constant (9.81 m/s^2) and h is the drop height (m) [14]. The impact energy level of a stainless-steel ball for five treatments was calculated as shown in Table 2. The highest impact energy value from a height of 0.6 m for five drops was 7 357.50 J, followed by 3 678.75 J (0.3 m + 5 drops), 1 471.50 (0.6 m + 1 drop) and 735.75 J (0.3 m + 1 drop). After impact testing, the fruit were stored at room temperature (25 °C under 70 % RH) and checked for quality measurement every day (24 h) for four days.

Table 2 – Impact energy for different drop heights and number of drops.

Treatment	Impact energy (J)
Control (no drop)	0.00
0.3 m + 1 drop	735.75
0.3 m + 5 drops	3 678.75
0.6 m + 1 drop	1 471.50
0.6 m + 5 drops	7 357.50

Before impact bruising determination, the bruised guava sample from the simulated impact test was peeled using a sharp knife with peel thickness of approximately 0.9 mm to reveal browning of the flesh (Fig. 1). It is noted that the guava was peeled to reveal either translucent incidence (wet bruising) or browning incidence. Also, the sampling sample for color determination at bruise region was explained by Htike et al.'s method [27].

Bruise area (BA) and bruise volume (BV): BA and BV are commonly used to measure the amount of fruit bruise damage. The BA and BV of each fruit were determined based on impact bruising in apple [13] and calculated by Eqs. (1) and (2).

$$BA = \pi/4\ (ab) \tag{1}$$

$$BV = \pi d/24\ (3ab + 4d^2) \tag{2}$$

where a and b are the major axes of the bruise elliptical and d is bruise depth measured from peel thickness [7]. These bruise parameters, introduced in Fig. 2, were measured with a digital caliper (RS PRO 150 mm, RS Components Pte ltd Robinson Road, Singapore) with ± 0.01 (mm) accuracy.

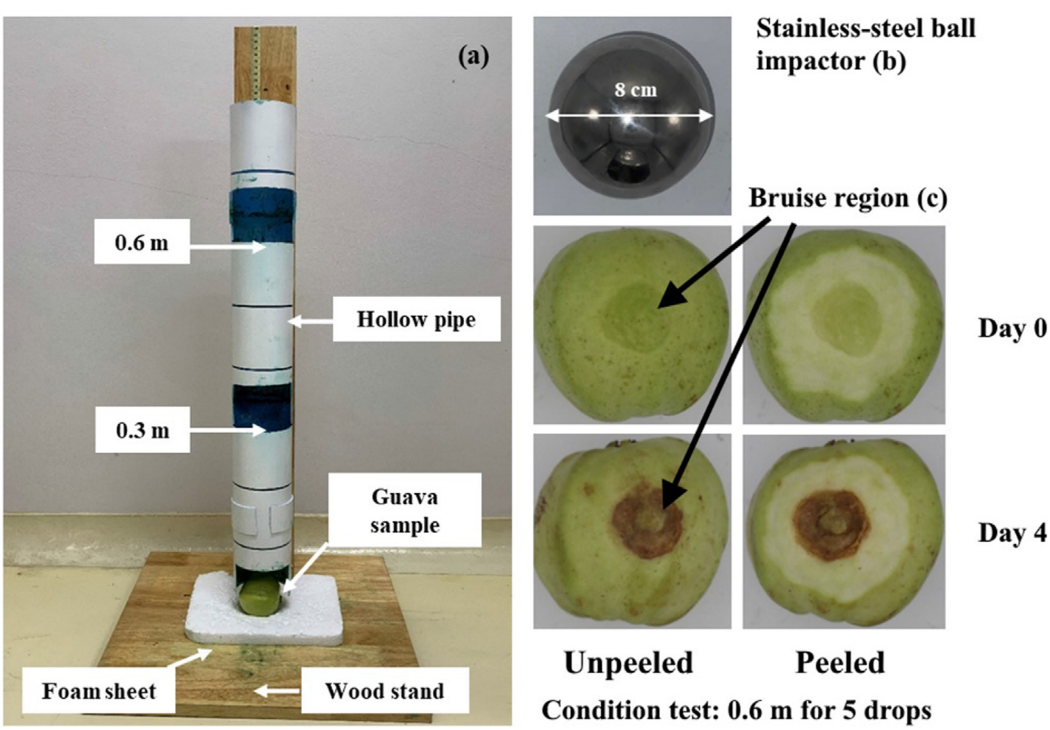

Fig. 1 – Experimental setup of simulated laboratory bruise impact test (a), stainless-steel impactor (250 g, diameter 8 cm) (b) and bruise region of guava on day 0 and 4 (c). The impact test was adapted following Hussein [14].

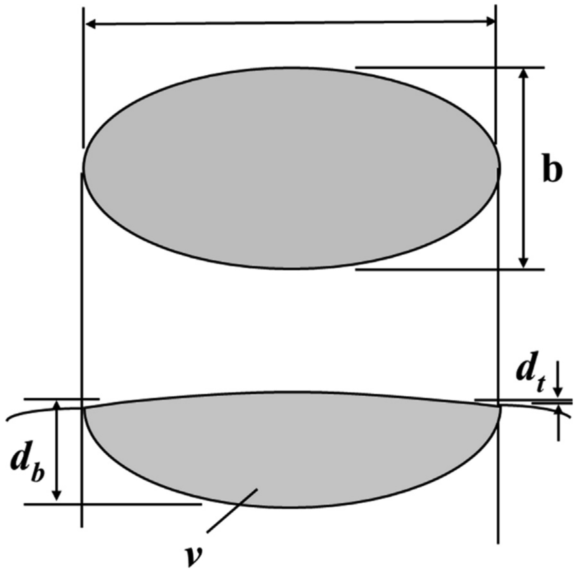

Fig. 2 – Elliptical method for determining BA and BV [13].

Bruise susceptibility (BS): BS (mm^3/J) was calculated as the ratio of BV (mm^3) to the impact energy *E* (J) by Eq. (3) [10,12,36].

$$BS = BV/E \quad (3)$$

Specific bruise susceptibility (SBS): To measure the index of BS, SBS ($mm^3/J \cdot g$) was determined by Eq.(4) [36].

$$SBS = BS/mF \quad (4)$$

where mF is the mass of fresh fruit specimen (g).

Bruise score: The peeled guava was visually assessed for bruise score adapted from the bruise score of apple [37] based on a 4 point scale as 1 No apparent bruise, 2 Light bruise with no defined edge, 3 Moderately dark brown bruise with a well-defined edge, and 4 Dark brown bruise, as shown in Table 3.

Table 3 – Bruise damage visual rating score.

Rating score	Description	Image
1	No apparent bruising	
2	Light brown bruise with no defined edge	
3	Moderately dark brown bruise with a well-defined edge	
4	Dark brown bruise	

2.3. *Pulp color at bruising region*

A colorimeter (model: CR-10 color reader, Osaka, Japan) was used to measure bruise lightness (L^*), redness (a^*), yellowish (b^*) and chroma (C) based on CIELab; L^* (lightness) as black (0) and white (100), a^* (red to green) as red (positive value) and green (negative value) and b^* (yellow to blue) as yellow (positive value) and blue (negative value). The chroma (C) defines color saturation [38].

2.4. *Image analysis*

After impact testing, the bruise region on the fruit surface was positioned under a square light box (UDIOBIZ 40D, Bangkok, Thailand), size 40 × 40 × 40 cm, adjustable light, pocket studio with 4 rows of LED as a light source intensity of 9.6×10^5 lm/m^2 using a light meter (Tenmars TM-204, Taipei, Taiwan, China). All guava images were taken from the top of the light box with a uniform distance of 40 cm between the guava and the camera lens. A digital mirrorless camera (Canon EOS M50, 15–45 mm, Tokyo, Japan) was used to capture the guava images. Camera settings were on manual mode, auto focus, lens capture at f 7.1, with 1/250 shutter speed and ISO 100. Image analysis of guava bruise damage was performed using ImageJ software (version 1.51j8, NIH, Bethesda, MD, USA). The original image files (6 000 × 3 368 pixels) were saved into JPEG format with resolution of 72 dpi. All original images were pre-processed, cropped and resized, with threshold color adjusted before analysis. The color threshold method was applied on cropped images for region of interest (ROI) as bruising region selection. The ROI was then calculated as percentage of bruise region corresponding to whole flesh area. ROI data obtained from image analysis were converted into bruise scales (Fig. 3).

The FD values were determined by converting cropped RGB images into 8-bit images. Surface plots of 8-bit images were calculated to determine the intensity of fruit bruise

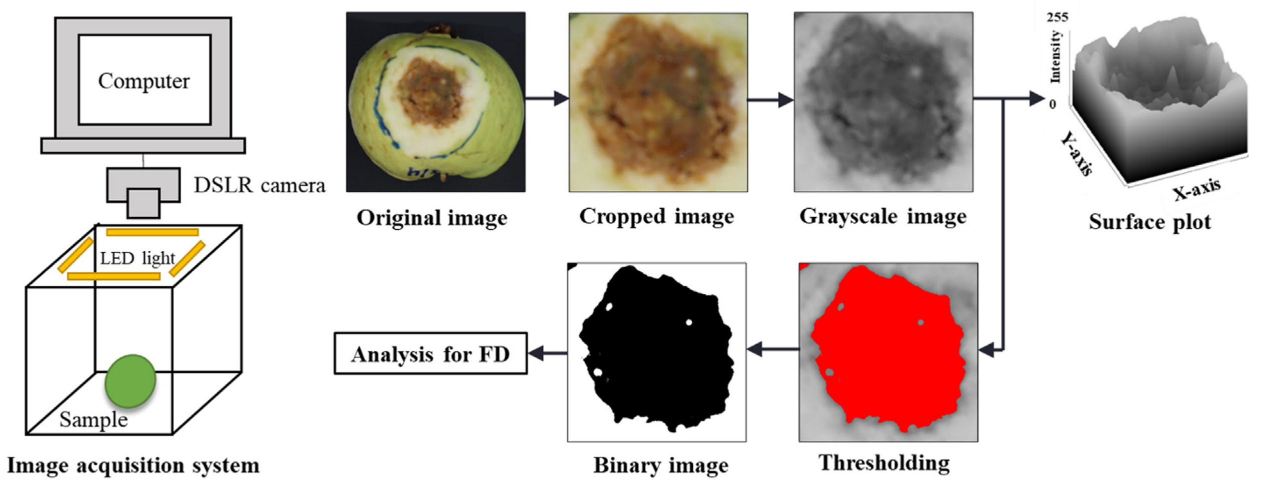

Fig. 3 – Experimental setup and image analysis procedure for bruise determination.

damage. The bruise damage region was then separated using the threshold method. The selected area of bruise was converted into a binary image before determining FD values. A box counting method was applied to determine the FD value following the method used in Fig. 4.

2.5. *Model prediction and validation testing*

FD value was determined and polynomial fitting with coefficient determination value (R^2) for five treatments followed Eq.(5).

$Y = b_0X^2 + b_1X + b_3$ (5).

where Y is the predicted FD value, X is storage time (day), X^2 is the square of X and b_0 and b_1 are constants.

Fruit samples with three impact bruises (replicates) in each treatment were used to validate testing for five polynomial equations with R^2 validation ($R^2{}_{val}$). Validation of impact bruising in guava focused on the FD values from image analysis.

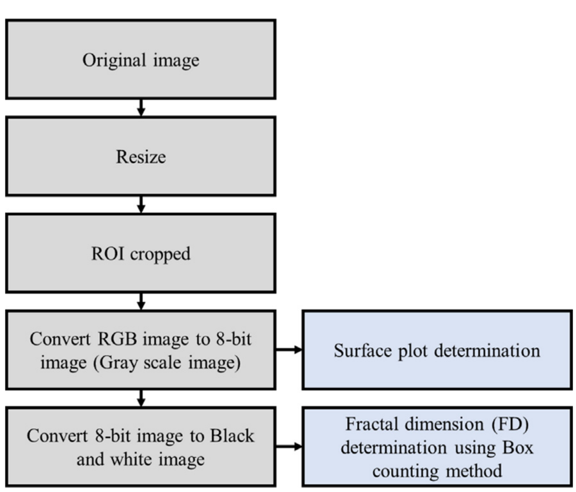

Fig. 4 – Image analysis flow for FD determination.

2.6. *Data analysis*

SPSS for Windows version 20 (SPSS Inc., Chicago, IL, USA) was used for statistical analysis. Data analyses for impact bruising parameters, color indices and FD values were compared by means (α = 0.05) using Tukey's HSD post hoc test. Fractal image analysis of impact bruise incidence was investigated using ImageJ software (version 1.51j8). Impact bruising parameters, color indices and FD values were analyzed using Pearson's correlation coefficient (*r*) at significant difference $p < 0.01$.

3. Results and discussion

3.1. *Pulp color at bruising region*

Results in Fig. 5 show that increase in drop height and number of drops significantly affected the values of all color attributes (L^*, a^*, b^* and C) ($p < 0.05$). Control treatment (no drop) had significantly higher values of L^*, a^* b^* and C than the other four treatments after storage at 25 °C under 70 % RH for four days ($p < 0.05$). After fruit impact damage, enzymatic browning reaction and resulting discoloration occurred inside cells, following cell membrane damage and release of cell contents into intercellular spaces [39]. In this study, five drops from a height of 0.3 and 0.6 m showed the lowest color values (L^*, a^*, b^* and C) concurring with results of highest impact BS (Table 4). Major bruise damage to guava was caused by the number of drops, resulting in the highest peel color changes compared with the control (no impact bruise). The number of drops was also a major factor affecting impact damage in pomegranate fruit. Drop heights of 0.2, 0.4 and 0.6 m were tested twice and compared with the control (no drop). No significant difference in bruise score was recorded between height of 0.2 m (twice) and no drop [40]. Drop conditions in 'Montenegrina' tangerines were tested at heights of 0.4 and 0.6 m or 0.8 and 1 m, twice at each height. No significant differences of hue value were found at drop heights of 40 and 60 cm or drop heights of 0.8 and 1 m [41]. Impact damage browning of guava fruit was investigated by L^*, a^* and b^* val-

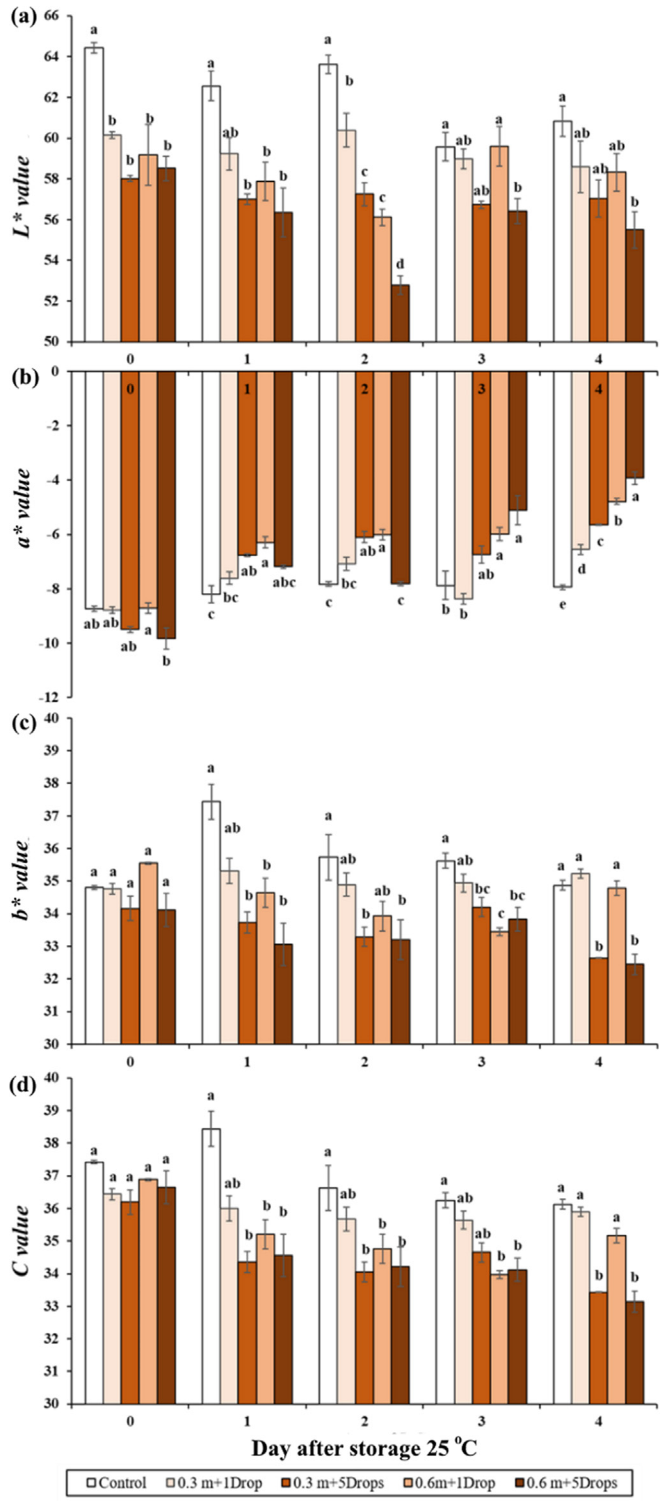

Fig. 5 – Pulp color *L(a), *a** (b), *b**(c) and *C* (d) values of bruise damage of guava fruit from day one to day four after storage at 25 °C under 70 % RH. Different letters in each day mean significant differences at $p < 0.05$ using Tukey's HSD post hoc test. Values are mean ± S.E. from five replications.**

ues (Fig. 5). A higher correlation coefficient (*r*) was determined between bruise parameters and *L**, *a** and *b** color values than the *C* value (Table 5). In this study, major and minor factors of impact guava bruising were the number of drops and drop heights, respectively. Therefore, postharvest handling of guava should be conducted with care.

Table 4 – Bruise assessment parameters of guava fruit stored at 25 under 70% RH for four days.

Days after storage at 25 °C	Treatment	Fruit mass (g)	Bruise area (BA) (mm^2)	Bruise volume (BV) (mm^3)	Bruise susceptibility (BS) (mm^3/J)	Specific bruise susceptibility (SBS) (mm^3/J·g)	Bruise score
1	Control (no drop)	255.32 ± 19.50^{a}	0.0 ± 0.0^{d}	0.0 ± 0.0^{c}	0.00 ± 0.00^{d}	0.000 ± 0.000^{d}	1.0 ± 0.0^{d}
	0.3 m + 1 drop	247.04 ± 10.13^{a}	149.3 ± 4.4^{c}	712.0 ± 74.9^{c}	0.97 ± 0.10 ^{cd}	0.004 ± 0.000 ^{cd}	2.4 ± 0.2^{c}
	0.3 m + 5 drops	237.36 ± 8.54^{a}	281.0 ± 55.3^{b}	1 906.2 ± 374.3^{b}	2.57 ± 0.51^{b}	0.011 ± 0.002^{b}	3.2 ± 0.2^{b}
	0.6 m + 1 drop	257.68 ± 15.18^{a}	329.9 ± 18.4^{b}	2 069.5 ± 205.1^{b}	1.41 ± 0.14^{c}	0.006 ± 0.001^{c}	3.4 ± 0.2^{ab}
	0.6 m + 5 drops	266.72 ± 9.08^{a}	633.0 ± 24.1^{a}	6 131.2 ± 281.7^{a}	4.17 ± 0.19^{a}	0.016 ± 0.001^{a}	4.0 ± 0.0^{a}
2	Control (no drop)	246.8 ± 14.02^{a}	0.0 ± 0.0^{d}	0.0 ± 0.0^{d}	0.00 ± 0.00^{d}	0.000 ± 0.000^{b}	1.0 ± 0.0^{c}
	0.3 m + 1 drop	247.16 ± 7.49^{a}	151.0 ± 15.9^{c}	790.3 ± 113.8^{d}	1.07 ± 0.15^{c}	0.004 ± 0.001^{b}	2.4 ± 0.2^{b}
	0.3 m + 5 drops	249.7 ± 15.13^{a}	406.0 ± 36.0^{b}	3 116.9 ± 325.4^{b}	4.24 ± 0.44^{a}	0.017 ± 0.003^{a}	3.4 ± 0.2^{a}
	0.6 m + 1 drop	278.68 ± 9.77^{a}	315.4 ± 27.9^{b}	2 164.5 ± 151.9^{c}	1.47 ± 0.10^{c}	0.005 ± 0.001^{b}	3.6 ± 0.2^{a}
	0.6 m + 5 drops	227.76 ± 10.75^{a}	596.3 ± 50.4^{a}	4 483.3 ± 305.0^{a}	3.05 ± 0.21^{b}	0.014 ± 0.001^{a}	4.0 ± 0.0^{a}
3	Control (no drop)	279.16 ± 9.59^{a}	0.0 ± 0.0^{d}	0.0 ± 0.0^{c}	0.00 ± 0.00^{c}	0.000 ± 0.000^{c}	1.0 ± 0.0^{c}
	0.3 m + 1 drop	252.4 ± 12.58^{a}	137.4 ± 5.9^{c}	700.2 ± 74.4^{c}	0.95 ± 0.10^{b}	0.004 ± 0.000^{b}	2.2 ± 0.2^{b}
	0.3 m + 5 drops	247.14 ± 14.79^{a}	310.5 ± 35.8^{b}	1 993.5 ± 295.7^{b}	2.71 ± 0.40^{a}	0.011 ± 0.001^{a}	3.4 ± 0.2^{a}
	0.6 m + 1 drop	241.7 ± 18.27^{a}	279.8 ± 28.0^{b}	1 515.8 ± 228.4^{b}	1.03 ± 0.16^{b}	0.004 ± 0.001^{b}	3.6 ± 0.2^{a}
	0.6 m + 5 drops	247.08 ± 6.10^{a}	562.7 ± 20.1^{a}	3 896.1 ± 197.7^{a}	2.65 ± 0.13^{a}	0.011 ± 0.001^{a}	4.0 ± 0.0^{a}
4	Control (no drop)	268.24 ± 7.36^{a}	0.0 ± 0.0^{c}	0.0 ± 0.0^{b}	0.00 ± 0.00^{c}	0.000 ± 0.000^{c}	1.0 ± 0.0^{c}
	0.3 m + 1 drop	264.52 ± 11.31^{a}	119.0 ± 9.2^{c}	546.0 ± 46 ^{cd}	0.74 ± 0.06^{bc}	0.003 ± 0.000^{c}	2.4 ± 0.2^{b}
	0.3 m + 5 drops	248.18 ± 12.83^{a}	334.9 ± 37.1^{b}	1,937.6 ± 280.1^{b}	2.63 ± 0.38^{a}	0.011 ± 0.002^{ab}	3.4 ± 0.2^{a}
	0.6 m + 1 drop	251.78 ± 12.63^{a}	315.1 ± 27.1^{b}	1,847.6 ± 64.0^{bc}	1.26 ± 0.04^{b}	0.005 ± 0.000^{bc}	3.6 ± 0.2^{a}
	0.6 m + 5 drops	235.26 ± 17.0 ^{a}	615.6 ± 74.5^{a}	4 982.6 ± 631.8^{a}	3.39 ± 0.43^{a}	0.015 ± 0.002^{a}	4.0 ± 0.2^{a}

Mean values presented as mean ± S.E. for 5 replications in the same column followed by a different superscript letter (a, b, c or d) is significantly different ($p < 0.05$) using Tukey's HSD post hoc test.

Table 5 – Pearson correlation coefficients (*r*) between bruise assessment parameters of guava fruit and image analysis of FD and L^*, a^*, b^* and *C* values.

Bruising parameters	FD	L^*	b^*	C	a^*
Bruise scores	−0.676**	−0.657**	−0.677**	−0.663**	0.604**
BA	−0.794**	−0.660**	−0.656**	−0.607**	0.579**
BV	−0.745**	−0.615**	−0.627**	−0.532**	0.473**
BS	−0.672**	−0.605**	−0.629**	−0.556**	0.428**
SBS	−0.667**	−0.580**	−0.613**	−0.539**	0.427**

** = significantly correlated at $p < 0.01$.

3.2. *Bruise susceptibility of guava fruit*

The accumulation of impact energy by dropping the steel ball from different heights and number of drops at one or five significantly affected increase of BA and BV in guava fruit (Tables 2 and 4). Most drop height tests in round fruit (apple and pomegranate) were examined in a range of 0.05 to 0.3 m [13,14,40]. In this study, guava fruit weight for sample testing showed no significant difference. The drop test from 0.6 m drop height with five drops had the highest BA, BV, BS, SBS values and bruise score, followed by dropping from 0.3 m with five drops, dropping from 0.6 m with one drop and from 0.3 m with one drop (Table 4). Bruise results indicated highest impact energy at 0.6 m for five drops (Table 2). This finding concurred with previous impact fruit studies by dropping from different heights and number of drops [13,14,42]. Increasing the drop height (or impact energy) elevated the potential for bruise damage in pomegranate [12], kiwifruit [43] and peach [13]. Drop height and number of drops also influenced increase of bruise susceptibility in apple [13], pomegranate [14] and tomato [18].

3.3. *Image analysis for bruise determination*

The FD values were analyzed by converting cropped RGB images and calculated to view the intensity of fruit bruise damage. The bruise damage region was cropped and then separated using the threshold method. The selected BA was converted into a binary image before determining FD values using a box counting method. Image analysis for impact damage of guava after the drop test and storage at 25 °C under 70 % RH for two days (Fig. 6) and four days (Fig. 7). Impact damage of the pulp surface was visibly presented in BA and BV by image analysis. A greater impact bruise showed as a deeper surface plot image (Figs. 6 and 7), relating to increased impact energy (Table 2) and period of storage (Fig. 7).

Using image analysis, FD values were determined for lightness and darkness of the surface [23] to assess bruising or

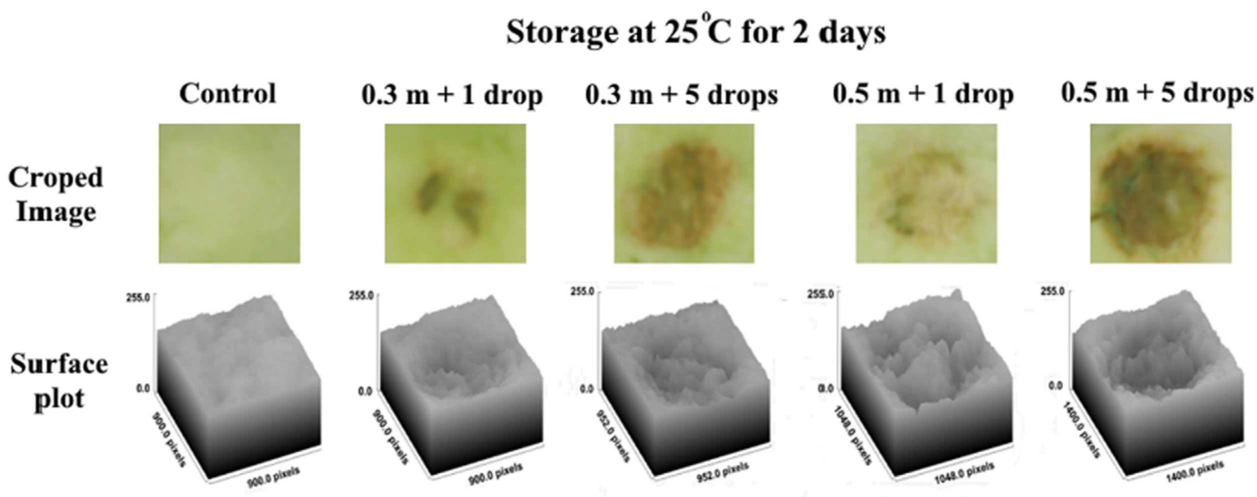

Fig. 6 – Image analysis for FD value of cropped image and surface plot of impact damage to guava fruit after drop test and storage at 25 under 70% RH for two days.

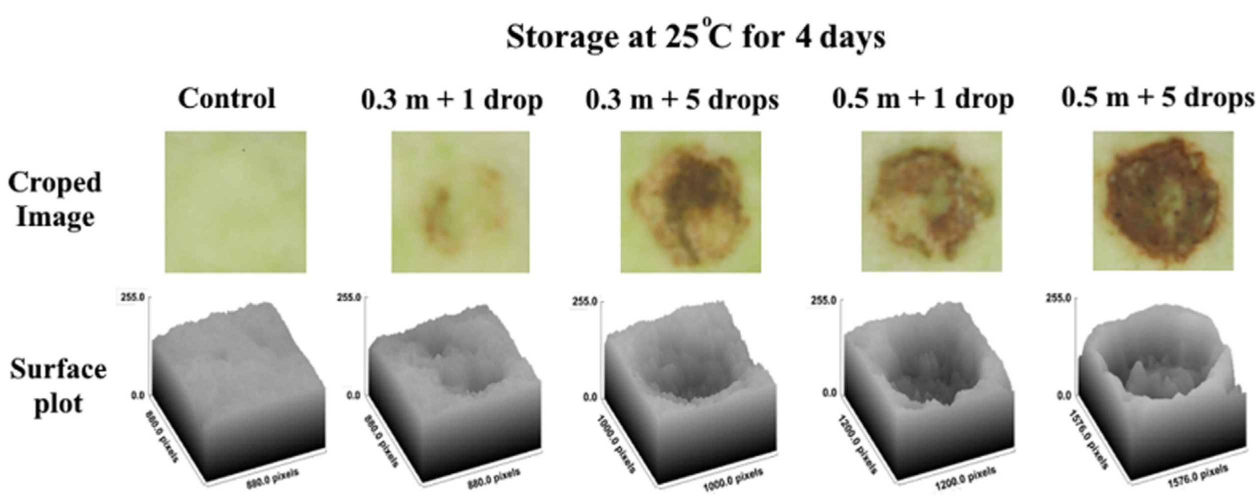

Fig. 7 – Image analysis for FD value of cropped image and surface plot of impact damage to guava fruit after drop test and storage at 25 under 70% RH for four days.

browning of the fruit. Fractal modeling was effectively applied to determine the intensity of flesh browning and its color change to provide a better understanding of enzymatic chemical changes and their location within fruit flesh [24].

The FD value of impact bruising in guava gradually decreased with increase of all bruise parameters and time duration after storage, except for the control (no drop) (Fig. 8 and Table 4). The control exhibited highest FD values (1.944 and 1.942) than the other four impact bruise treatments. The lowest FD value was observed at the two height levels of 0.3 m (1.930) and 0.6 m (1.932) with five drops (Fig. 8). Most previous researchers conducted fruit quality evaluation using the FD method to assess internal browning, color change in flesh and defects in pear [44], banana [23] and apple [24]. The FD method showed accuracy for avocado fruit browning [29], while increased uniformity of the browning area resulted in decreased FD value in pineapple [26]. A non-homogenous change color intensity distribution resulted in a higher FD value, while homogenous change resulted in a lower FD value in avocado fruit [29]. However, only study of the FD method for impact bruise evaluation has been conducted for guava under different impact bruising tests and storage temperature conditions. The result showed that a higher impact bruising exhibited a lower FD value. For example, at the same level of impact energy (E = 7 273.60 J), a drop height of 0.6 m for five drops for storage at 30 °C gave the lowest FD value (1.900) as the deepest surface plot image. While the drop test from the same drop height (0.6 m) for 5 drops (E = 7 273.60 J) exhibited a higher FD value (1.910) due to a lower storage temperature at 10 °C [27]. In this study, the period of storage time affected a lower FD value. Thus, a reduction of FD value caused an increase of drop height, number of drops, storage temperature and storage time. To the best of our knowledge, this is the second study reporting the advantage of FD techniques for impact bruise analysis in guava. Results confirmed that FD analysis has potential for

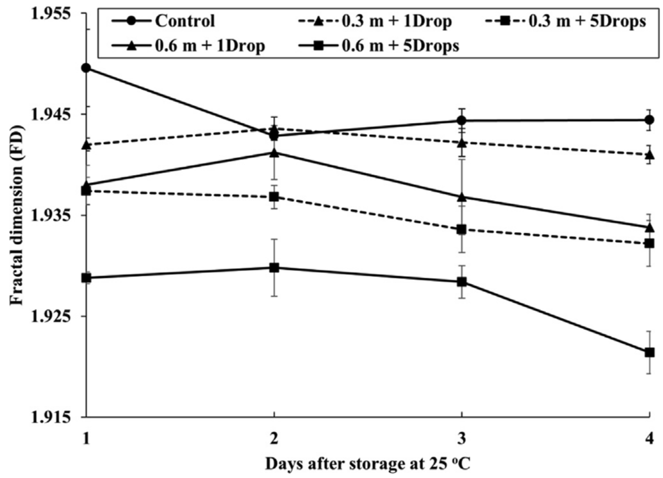

Fig. 8 – Impact bruise damage of guava fruit based on FD. Values are mean ± S.E. (error bar) from five replications.

Table 6 – Coefficient of determination (R^2 and R^2_{val}) and polynomial equations of guava fruit for different drop heights and numbers of drops.

Treatment	Polynomial equation	R^2	R^2_{val}
Control (no drop)	$Y = -0.0014X^2 - 0.0089X + 1.9565$	0.80	0.87
0.3 m + 1 drop	$Y = -0.0007X^2 + 0.0031X + 1.9398$	0.85	0.83
0.3 m + 5 drops	$Y = -0.0002X^2 - 0.0009X + 1.9387$	0.95	0.88
0.6 m + 1 drop	$Y = -0.0015X^2 + 0.0060X + 1.9340$	0.85	0.76
0.6 m + 5 drops	$Y = -0.0020X^2 + 0.0076X + 1.9230$	0.99	0.92

determination of impact bruising in guava for different bruise severities and storage times.

3.4. *Correlation between color features and bruise indices*

Results of the correlational analysis are compared in Table 5. The correlation coefficient (*r*) between FD and bruise parameters was higher than for all color values (L^*, a^*, b^* and *C*), particularly BA ($r = -0.794$) and BV ($r = -0.745$), while L^*, a^* and b^* values showed greater correlation between bruise parameters than *C* values. FD value indicated good correlation between impact bruise damage in guava than all color parameters. This finding supported previous research into the relationship between FD, L^* and environmental exposure, showing patterns of redness spreading related with non-homogenous color changes on the surface of papaya slice, clearly exhibited by 65 % ripe papaya [45]. Lightness parameters decreased when FD value increased, indicating greater complexity in the distribution of L^* values in the selected area analyzed during enzymatic browning in apple [24]. Thus, more research in impact bruising of guava or other fruit is required to determine the efficacy of FD techniques for mechanical damage caused by different external factors in fruit bruise sensitivity.

3.5. *Model prediction and validation testing of FD*

A good polynomial equation relationship was obtained between FD for impact bruise assessment of guava fruit in each treatment during storage for four days (Fig. 8 and Table 6). The lowest R^2 value (0.800) occurred in the control (no drop) due to no impact bruise damage on guava pulp. Among the other four treatments, five drops from heights of 0.3 and 0.6 m (0.948 and 0.988) had higher R^2 values than a single drop (0.851 and 0.855), respectively. The validation results of five R^2_{val} values were 0.87 (control), 0.83 (0.3 m + 1 drop), 0.88 (0.3 m + 5 drops), 0.76 (0.6 m + 1 drop) and 0.92 (0.6 m + 5 drops). Thus, a higher of both R^2 and R^2_{val} at five drops exhibited a higher accuracy for bruise prediction by FD value with greater bruise susceptibility (Table 6). For type of prediction modeling in fruit bruising, linear regression showed assessment and prediction with high R^2 value (>0.91) in apple [24], kiwifruit [43] and tomato [42]. A good linear regression equation for bruise assessments was also observed [42,43,46]. However, no reports are available showing polynomial equation relationship between FD and impact bruise damage assessment in other fruit.

4. Conclusion

Results showed that number of drops had more influence on ‘Gim Ju’ guava impact bruising than drop heights. Highest browning, as color changes and bruise attributes, was found at a height of 0.6 m for five drops, followed by a height of 0.3 m for five drops. Interestingly, image analysis of FD values showed higher potential than color measurement to evaluate impact bruise damage of guava fruit, particularly BA and BV. Findings offer science-based tools to assist in improving fruit quality assessment from impact bruising or mechanical damage in fruit using fractal image analysis. However, further research is required to investigate and apply FD analysis for BA and BV assessment in spherically shaped fruit such as apple, pomegranate and peach using simulated impact testing.

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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