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Comparison of the mass tissue strength of strawberry fruit between vertical and horizontal compaction

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Abstract

Strawberries have very thin skin that is prone to damage during post-harvest handling. The strength of this fruit mass tissue has a difference between vertical and horizontal directions. Therefore, this study aimed to compare the strength of the strawberry mass tissue between vertical and horizontal directions using a compressive test at different speeds and compressibility levels. The research was conducted by placing a load on the sample from the vertical and horizontal directions. The variations in compression speed were 2, 4, and 6 mm/s, and the compressibility levels were 6, 12, 18, 24, and 30%, respectively. The results showed that the compacting from the vertical direction obtained a combined mechanical response between the fruit structure and mass tissue cells, while from the horizontal direction the mechanical response was only obtained from the fruit structure. Along with the duration of the compacting, mass tissue damage has started to occur. In this phase, the fruit cells begin to break down in the skin causing the mass tissue damage to decrease. The results of this study can be used to develop a more efficient and effective packaging model for strawberries that has never been disclosed before.

1. Introduction

Fruit mass tissue damage is one of the most critical attributes in evaluating consumer acceptance of the quality of strawberry fruit (*Fragaria ananassa* Duch.) (Rosnah *et al.*, 2020; Huang *et al.*, 2020). This fruit is very susceptible to damage during its post-harvest quality handling (Liang *et al.*, 2020). Damage can occur during picking in the land, the distribution process to traders and consumers, and the storage process in the supply chain (La Scalia *et al.*, 2016; Kelly *et al.*, 2019; Ha *et al.*, 2020). Bruised damage can cause accelerated damage to the whole fruit during subsequent handling (Li and Thomas, 2014). Many fruits with seemingly minor damage during harvest are then discarded by traders which results in waste and can affect economic benefits for farmers and traders (Yan *et al.*, 2019).

For food technology, damage to fruit tissue is the behaviour of tissue damage to cell mass when the fruit was exposed to excessive impact (Li, Andrews and Wang, 2017; Horison *et al.,* 2019). Fruit mass tissue damage is highly dependent on fruit texture (Sirisomboon *et al.*, 2012). Therefore, it is very important to measure the mass tissue damage of the fruit to assess the quality of postharvest fruit (Duarte-Molina *et al.*, 2017; Contigiani *et al.*, 2018). Several researchers have previously estimated the tissue damage to the fruit mass during the harvesting process (Li *et al.*, 2015; Li, Miao and Andrews, 2017). The results showed that the hardness and strength of the tomato tissue tested by the puncture method using a probe varied between 0.37 and 2.25 MPa and 0.04 and 11.58 MPa.

Food loss of nutritional content due to mass tissue damage greatly affects consumer acceptance and purchasing power. Fruit that has been damaged is sold at a cheap selling price. Li and Thomas (2014) reported that fruit tissue damage resulted in price reductions of up to 50%. An effort to minimize the damage to mass tissue in the fruit is an important thing to do in order to maintain the quality and efficiency of agricultural products. Previous studies related to causing damage to the surface of the fruit have been investigated by Li *et al*. (2015) by storing the fruit for several days and then evaluating it by touch. Jones (2010) described a method for evaluating bruises on tomatoes using mechanical impact parameters related to the energy absorbed. Brinnel *et al.* (2020) reported that damage mechanics can provide an adequate description of ductile failure in small-scale experiments. Besides, there are several studies on the calculation of the volume of tissue damage to the mass of fruit after harvest by measuring fruit anatomy, such as apples

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(Celik *et al.*, 2011), oranges (Ihueze and Mgbemena, 2017), passion fruit (Ansar *et al.*, 2019), but this method is not suitable for strawberries because of the colour of the mass tissue, the broken and the undamaged look the same.

Aliasgarian *et al.* (2015) reported that the 'Selva' variety of strawberries cannot be sold if the skin has abrasions or bruises on the surface and more than 50% of the strawberries cannot be sold due to damage caused by impact during transportation. Chaiwong and Bishop (2015) reported that a vibration frequency ranging from 3 to 5 Hz affected the quality of the 'Elsanta' strawberry. Kelly *et al.* (2019) explained that the quality of the strawberries can be maintained by keeping the temperature constant during post-harvest handling.

The results of research on the quality of strawberries were more dominated by changes in fruit quality during post-harvest, such as the freshness of strawberries depending on the fruit variety (Pham and Liou, 2017; Zeliou *et al.*, 2018), storage time and conditions (La Scalia *et al.*, 2016), storage method (Contigiani *et al.*, 2018; Yan *et al.*, 2019; Zhang *et al.*, 2018), while the effect of vibration affects fruit firmness (Chaiwong and Bishop, 2015). The firmness of the fruit is a physical characteristic that describes the most important qualities of a strawberry. Many factors influence the firmness of strawberries, such as genetics, growing conditions, level of maturity, size, postharvest handling, and internal temperature (Doving and Mage, 2002). Fruit strength data is also influenced by the test method used and until now there is no standard test method for the texture strength of strawberries (Fu *et al*., 2008).

Information about the damage to the mass tissue of strawberries caused by compression, the direction of loading, and the percentage of fruit mass tissue damage is still limited. As a result, it is difficult to quantitatively assess the mass tissue damage and deformation of the strawberry fruit. According to An *et al.* (2020) strawberries are very susceptible to mechanical damage when subjected to loads, especially in the direction of the radial axis. This gap also hinders the development of non-destructive methods for fruit quality analysis (Zude-Sasse *et al.*, 2019) and limits the opportunity to investigate the influence of external stresses during harvest (Zhuang *et al.*, 2019), appropriate packaging and transportation methods for distribution processes (Li, Andrews and Wang, 2017). Therefore, this study aimed to compare the strength of the strawberry fruit mass between the vertical and horizontal directions using a compressive test at different speeds and levels of compressibility.

2. Materials and methods

2.1 Materials

The ingredients used are strawberries with Sweet Charlie varieties. This fruit was obtained from agricultural farmers in Sembalun, East Lombok, Indonesia. The strawberry fruit sample used has a maturity level of 80%, measuring 3 × 3.5 cm with an average weight of 53.75 g (Figure 1). After being carefully transported to the Bioprocess Engineering Laboratory of the University of Mataram, West Nusa Tenggara, Indonesia, the fruit was then cleaned manually with water and checked again to make sure it was not damaged and not infected by bacteria. The test was carried out within 24 hrs at room temperature (29±1°C) and RH 60-65%.

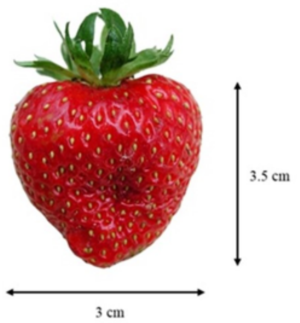

Figure 1. The strawberry size used for testing purposes

2.2 Deformation test

The sample deformation test used the CT3 texture analyzer (model of CT3-100, brand of Brookfield, USD) with a load range of 0-100 g (Figure 2). The type of probe used was cylindrical. Loading was done from the vertical and horizontal directions (An *et al.,* 2020). The variations in compression speed are 2, 4, and 6 mm/s, and the compressibility levels are 6, 12, 18, 24, and 30%, respectively. Each test was repeated 3 times. The deformation curve of the test results was recorded in real-time.

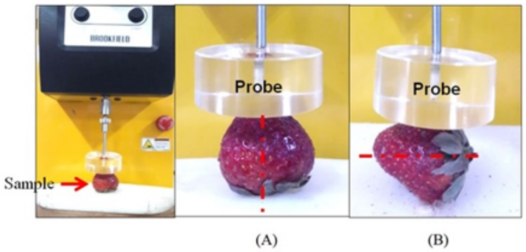

Figure 2. Strawberry fruit deformation test, (A) compression from the vertical direction, and (B) compression from the horizontal direction.

2.3 Determination of the percentage of fruit deformation

The percentage of fruit deformation after compression can be calculated using Equation (1) (Tabacu and Ducu, 2020):

$$\varepsilon c = \frac{\Delta L}{L} \times 100 \quad (1)$$

where εc is the fruit deformation (%), ΔL is the difference in sample length before and after testing (mm), and L is the initial length of the sample (mm) (depending on the direction of compaction).

2.4 Determination of the percentage of fruit mass tissue damage

After being compressed, each sample was halved and then placed on a table for 5 hrs to wait for the enzymatic browning reaction. Furthermore, the tissue damage to the sample mass marked with brown colour was separated and then weighed using an electronic scale.

The ratio of water loss (η) during 5 hrs of storage for the unprocessed fruit group (control) was calculated using Equation (2) (An *et al.*, 2020):

$$\eta = \frac{m_0 - \dot{m}_0}{m_0} \quad (2)$$

Where m_0 is the initial mass of fruit before storage and $\dot{m}_0$ is the mass of fresh fruit after 5 hrs of storage in the control group.

The brown mass tissue was associated with the mass tissue of the fruit mass damaged during compression and the non-brown mass tissue was associated with the mass tissue of the fruit mass that was not damaged. Compressed fruit has the same rate of water loss within 5 hrs after splitting. Therefore, the m_4 mass of the damaged mass tissue in each sample and the percentage of damaged mass tissue (R) were calculated using Equations (3) and (4) (Xu *et al.*, 2006):

$$m_4 = m_1 - m_2 - m_3 = m_1 - m_1\eta - m_3 \quad (3)$$

$$R = \frac{m_4}{m_1} \times 100\% \quad (4)$$

where m_1 is the initial mass of fresh fruit in the experimental group (g), m_2 is the mass of water loss in the compressed fruit after 5 hrs of storage (g), m_3 is the mass of undamaged tissue mass in the compressed fruit after 5 hrs of storage (g), m_4 is the mass of tissue mass damaged in the compressed fruit after 5 hrs of storage (g), and R is the percentage of the mass of damaged fruit tissue after 5 hrs of storage (%).

2.5 Statistical analysis

Two-factor analysis of variance (ANOVA) using SPSS (Statistical Product and Service Solutions) version 16.0 to analyse the ratio of tissue damage to the mass of strawberries between the vertical and horizontal directions after being compressed with different compression speeds and levels of compressibility. The difference was considered significant if the probability value was less than 0.05 ($P<0.05$) (Ansar *et al*., 2020).

3. Results and discussion

3.1 Effect of compression direction on fruit mass tissue damage

Fruit compressed from the vertical direction showed less tissue mass damage when compared to the horizontal direction (Figure 3). This is presumably because the strawberry fruit is elliptical which causes the curvature contour in the horizontal direction to be much greater than in the vertical direction. As a result, the number of cells compressed in the horizontal direction is more than in the vertical direction and the damage in the horizontal direction is greater than in the vertical direction. The results showed that the compression direction had a significant effect ($P<0.05$) on the fruit mass tissue damage.

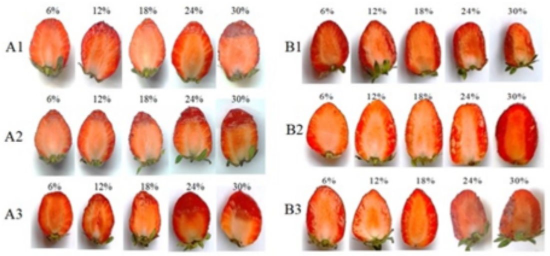

Figure 3. Fruit mass tissue damage after compression, (A1, A2, and A3) compression from the vertical direction, and (B1, B2, and B3) compression from the horizontal direction at velocities 2, 4, and 6 mm/s.

Fruit mass tissue damage always occurs in areas in direct contact with the probe. The mass tissue damage at the equator is always greater than that in the fruit stalk. This was related to the curvature of the fruit contour at the equator, where the contact surface was smaller than that of the fruit stalk. These results were in agreement with those reported by An *et al.* (2020) in which the percentage of fruit mass tissue damage was lower in the fruit stalk compared to the mass tissue damage that was near the probe which was compressed in the vertical direction.

At the beginning of the loading, the outer mass tissue more quickly receives the compressive force when compressed from the vertical direction because the outer layer was close to the fruit flower. When compressed from the horizontal direction, the probe exerts a compressive force on the outer mass tissue. Therefore, when the fruit was in the plastic deformation stage during compression, the peak force was higher from the vertical than in the horizontal direction. Besides, because the strawberry was elliptical, the curvature of the fruit from the vertical was much smaller than the contour from the horizontal. This shows that strawberries are more susceptible to mass tissue damage when loading was carried out from the horizontal direction than from the vertical direction.

At the time of loading the probe was only able to compress a small portion of the mass network that was from the vertical direction and compress the mass network more widely when loading from the horizontal direction. As a result, strawberries that experience a loading force from the horizontal direction show a higher resistance than from the vertical direction. These findings indicate that the percentage of tissue damage to the mass of strawberries can be minimized if the fruit was arranged vertically in the package. Similar results have been found by Sadrnia *et al*. (2008) for watermelons, Li *et al*. (2015) for tomatoes, Perez-Lopez *et al*. (2014) for peaches, and Liu *et al*. (2019) for apples.

When the fruit was compressed, the fruit cells at the bottom of the probe experience a high compression curve, while the adjacent cells experience tension or bending. The direction of compression has a significant effect on tissue damage to the fruit mass. The damage to the fruit mass tissue was greater in the horizontal direction than in the vertical direction. Compression from the direction of the vertical direction produces a combined mechanical response between the fruit structure and cell tissue mass. However, compression from the direction of the horizontal direction of the mechanical response only results from the structure of the fruit. These results were in agreement with those reported by Li *et al*. (2014) in which the compression from the horizontal direction only provides a mechanical response from the dense mass of biomaterial tissue as a result of which the fruit cell structure becomes weak.

This finding was very useful because evaluating the percentage of fruit mass tissue damage was tedious and challenging to produce accurate data, whereas the energy absorbed was easily measured by simply a compressive test. The same thing was revealed by Miraei-Ashtiani *et al*. (2019) that the tissue damage to fruit mass was closely related to fruit mechanics which can be measured quantitatively using the parameters of the energy absorbed.

3.2 Effect of compression speed on fruit mass tissue damage

The observational data showed that the compression rate had a significant effect on the tissue damage to the fruit mass. Fruit suffers a large percentage of damage at high loading speeds. Fruit compressed from the vertical direction and the horizontal direction always had a greater percentage of damage at a compression speed of 6 mm/s than at 4 and 2 mm/s (Figure 4).

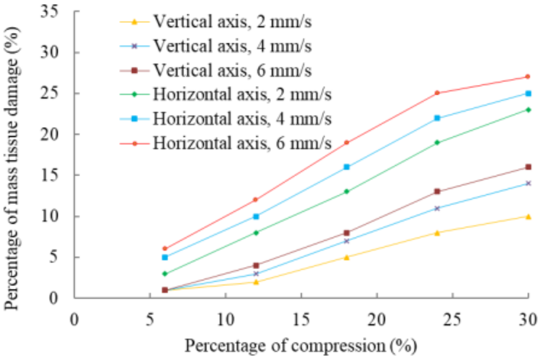

Figure 4. Percentage curve of fruit mass tissue damage at the compression rate of 2, 4, and 6 mm/s.

The results of the analysis of variance show that the F-count value (78.088) was greater than the F-crit value (2.776). This means that there was a significant effect ($P<0.05$) of compression speed on the damage to fruit mass tissue. When the fruit is compressed from the direction of the vertical or horizontal direction, the damage to the fruit tissue at a compression rate of 6 mm/s was always greater than that of 4 and 2 mm/s. This was presumably because when the fruit was compressed, the mass tissue of the fruit experiences a volume reduction in a short and fast time. Consequently, the fruit provides a high defensive force to the probe because the impulses applied are the same for all compression rates of 2, 4, and 6 mm/s.

Another thing that needs to be expressed was that the strawberry fruit was elliptical and when compressed at high speed, the compressed fruit cells get bigger (Figure 3). The percentage of damage gradually increases with increasing compression speed. The phenomenon of increasing the percentage of fruit mass tissue damage is similar to the results of studies reported by Kohyama *et al*. (2013) that the tissue mass of strawberries when compressed at high speed always shows large tissue damage. The tissue damage to the mass of strawberries compressed at high speed was greater than that compressed at low speed (Singh *et al*., 2014). Therefore, the process of distributing fruit from agricultural land to markets needs to be done carefully to avoid collisions. Based on these results, it was necessary to consider the compression load threshold to maintain the quality of the fruit during post-harvest handling, packaging, and transportation.

3.3 Effect of compressibility level on fruit mass tissue damage

The study showed that the compressibility level had a significant effect ($P<0.05$) on the percentage of fruit mass tissue damage (Figure 3). At the beginning of compression, the percentage of fruit mass tissue damage increases rapidly and then decreases slowly. The percentage of fruit mass tissue damage that is in direct contact with the surface of the probe contact area increases gradually during loading before permanent tissue damage occurs. Likewise, the number of compressed cells increases gradually, and in the end, the fruit undergoes 3 phases of deformation, namely elastic, plastic, and permanent mass tissue damage. The three-phase deformation of the fruit during compression has also been explained by Neto et al (2013) that when the fruit collides with each other, there will be a change in shape known as plastic deformation, elastic deformation, and a combination of both, namely shape deformation.

Based on the analysis of variance, it was known that the F-count value (450.571) was greater than the F-Crit value (3.838). This shows that the fruit has different cell structures due to the different physical characteristics of the fruit with different loading directions. This phenomenon is important as the basis for determining the fruit transport design model.

Collisions always occur during postharvest handling and transportation because the fruit at the bottom of the container can be subjected to additional compressive forces from the container. Fruit mass tissue damage can occur if the compressive force exceeds the threshold strength of the fruit mass tissue. Due to its viscoelastic nature, the mass tissue of the fruit can be damaged even with the slightest impact but occurs repeatedly (Link *et al*., 2018). The compression movement that occurs repeatedly consists of 2 models, namely compression between fruit and fruit and compression from solid to fruit.

3.4 Strawberry fruit deformation

The study showed that during compression, there was deformation and the surface contact area increases with increasing compression force (Figure 5). This phenomenon can be illustrated using a circular contact plane theory approach, where the size of the contact area is smaller more than the radius of the contact surface. Jahanbakhshi *et al.* (2018) have explained that contact plane theory can be used to predict the collision behaviour between 2 round pieces during compression, but it is difficult to measure and validate the compressive forces and fruit deformations that occur during compression.

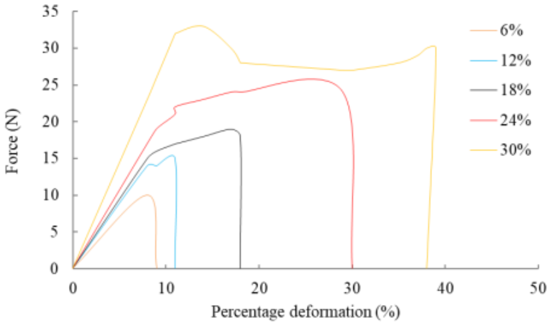

Figure 5. Deformation curve of the compressed strawberry fruit from the vertical direction at different speeds and compressibility levels.

The compressibility level was 6%, the deformation curve was close to linear and no brown color appeared on the longitudinal equatorial part of the fruit at any load (Figure 6). This showed that the compressibility level was 6% as the elastic deformation limit for compression in the direction of the vertical direction with velocities of 2, 4, and 6 mm/s. Before the inflection point, the deformation curve looks linear. After the inflection point was reached, the deformation percentage no longer increases, although the loading force tends to increase. However, the percentage of brown color in the longitudinal equatorial portion of each sample increased very rapidly with increasing fruit deformation.

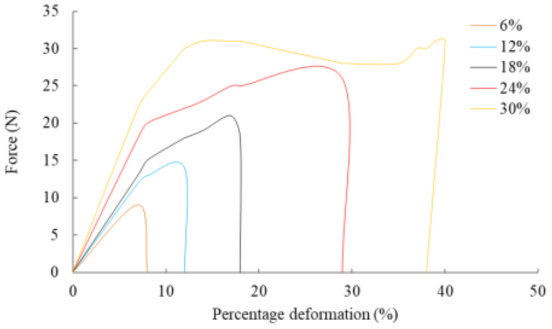

Figure 6. Deformation curve of strawberry which is compressed from the horizontal direction at different speeds and compressibility levels.

Figure 6 shows the deformation curve of a strawberry fruit compressed from the horizontal direction at different speeds and degrees of compressibility having a similar pattern to the compressed sample from the vertical direction, where the deformation of 6% was considered the elastic deformation limit. The inflection point was seen at a compression speed of 2 mm/s and a compressibility level of 6%. The point of this curve is the limit of the plastic deformation susceptibility of the sample to the load from the horizontal direction.

The compressibility level of 24% was the limit of the percentage of plastic deformation that causes damage to the inner tissue of the fruit when compressed from the horizontal direction at speeds of 2, 4, and 6 mm/s. When the compressibility level was more than 24% at a compression speed of 2 mm/s or 30% at a compression speed of 6 mm/s, the percentage of fruit brown increases with the increasing percentage of deformation. In contrast, the percentage of brown colour decreases at the longitudinal equator when the compressibility is less than 24% at a compression rate of 2 mm/s or 30% at a compression rate of 6 mm/s. The same study had reported by Braun and Ivanez (2020) that the difference in outcome between cell sizes was more pronounced at a 10% damage percentage. However, the difference between the three cell sizes shows a variation of not more than 6% and the highest percentage of damage was around 50%.

Another interesting phenomenon during compaction was that the combined mechanical response between the fruit structure and the mass tissue cells occurs in the vertical direction, whereas the compression from the horizontal direction was only obtained from the mechanical response of the fruit structure. In addition, the fruit undergoes 3 deformation phases, namely elastic, plastic, and permanent mass tissue damage. In the elastic deformation phase, the fruit has not been damaged. As compression time increases, permanent mass tissue damage begins to occur. In this phase, the fruit cells begin to break and break on the skin, causing damage to the fruit structure.

4. Conclusion

Strawberry fruit undergoes three stages of deformation during compression, namely elastic deformation, plasticity, and permanent damage to tissue mass. The amount of energy absorbed depends on the direction of the direction and the speed of compression, whereas the percentage of mass damaged depends only on the direction of the compression direction. Fruit mass tissue damage is greater when compressed from the horizontal direction than the vertical direction. Compression from the direction of the vertical direction produces a combined mechanical response between the fruit structure and cell tissue mass. However, in the horizontal direction, the mechanical response results only from the fruit structure.

The outer mass tissue of a strawberry is more susceptible to damage than the deep mass tissue. Therefore, the post-harvest handling process from agricultural land to the hands of consumers requires gentle handling to maintain fruit quality. The percentage of mass tissue damage of strawberries can be minimized if arranged vertically in the package. The percentage of fruit mass tissue damage obtained from this study can be used to predict changes in fruit volume non-destructively. These findings provide the information needed to develop a primary packaging design that can prevent damage to the strawberry mass tissue.

Conflict of interest

The authors declare that they have not a conflict of interest that could have appeared to influence the work reported in this paper.

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