The Effect of Impact Energy and Turgor Pressure on the Bruise Volume of BC Royal Gala Apples

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Abstract

Apple bruising is one of the major causes for economic losses for apple farmers in BC. In this study, the bruise threshold, bruise susceptibility, and bruise volume of the BC Royal Gala Apple were investigated as a function of impact energy. Impact energy was varied using a pendulum testing technique with regular height intervals of 2 cm. Additionally, turgor pressure was adjusted for by immersing the apples in water for 0, 1, and 18 hours, respectively. Impact energy and bruise volume were measured following the Bruise Thickness Method using the LoggerPro and ImageJ analytic softwares. The relationship between bruise volume and impact energy was analyzed using regression models on Excel. These models revealed that in general, apples with higher turgor pressures tend to have lower overall bruise volume when subjected to similar levels of impact energy. Apples with increasing turgor pressure also had the best fit for the model. The bruise threshold of Gala apples was measured to be 0.08 J and bruise susceptibility varied from $6.7 \text{ cm}^3 \text{ J}^{-1}$ in apples without water immersion to $2.31 \text{ cm}^3 \text{ J}^{-1}$ in apples immersed for 18 hours. Immersing apples in tap water for 18 hours was found to be an effective method to reduce apple bruise susceptibility.

Introduction

Apple bruising has always had serious ramifications for the apple industry, because the apple farmers experience huge economic losses every year due to apple bruising caused by mechanical damage. For instance, factors such as bruising led to 32 percent of food waste in the world in 2009 (Lipinski et al. 2013). Apples are usually bruised by dynamic forces in the transportation and handling process. In order to reduce the amount of bruising in apples and the loss of economic values due to bruised apples, significant amount of research was done on this subject in the past few decades.

In the previous research, researchers applied various methods, such as drop tests (Lewis et al. 2007), pendulum test (Bollen et al. 2001), and apple-apple impact test (Pang et al. 1992), to find the relationship between the impact energy and the bruised volume of apples. Most research, however, was done on the most common types of apples on the market, such as the Red Delicious, the Granny Smith or the Golden Delicious apples (Schoorl and Holt 1997). Along with the impact energy and bruising relationship, many variables, such as the effect of temperature, fruit ripeness and storage time, were investigated by researchers on the wide variety of apples as well. However, the effect of turgor pressure, or the amount of water present in apple cells on the bruised volume has not been investigated very much.

The large amount of research papers on the subject of apple bruising generated many different types of methods for the estimation and calculation of the volume of apple bruise. Most methods consist of estimating the bruised volume as a spherical or elliptical ball. Bollen et al. (2001) effectively summarized and evaluated all kinds of bruise volume estimation methods.
devised by many researchers in the past few years. Bollen et al. (2001) found that the Enclosed Volume Method and the Bruise Thickness Method proposed by Holt and Schoorl (1997) and Mohesenin (1986), respectively, are the two most accurate methods for apple bruise volume calculation.

The popularity of the Royal Gala apple in the North American market and the lack of research done on the effects of turgor pressure to the relationship of impact energy and bruise volume were the main reasons that motivated this study. Based on previous research, there is a consensus in that higher drop heights, thus larger impact energy, are related with larger bruised volumes in apples. However, there is not a definite consensus reached for the effect of various factors, including turgor pressure, on the extent of bruised volume in apples.

In this study, the relationship of the impact energy and bruising volume in the BC Royal Gala apples that are similar in size and radius of curvature will be investigated using the method of pendulum testing. The study will focus on finding a model of the relationship between impact energy and bruised volume in the BC Gala Apple. Along with this model, the impact threshold, or the maximum amount of energy the apples can absorb without bruising, will also be investigated. Bruise susceptibility or bruise resistance constant is the ratio between the bruised volume and impact energy, which indicates how easily fruits can be bruised. This constant will also be investigated. The effect of different turgor pressure in the Gala apple on the model, threshold and bruise susceptibility can be obtained as well.

Based on previous research done by Pang et al. (1992), the hypothesis of this experiment is that there will be a linear relationship between the impact energy and bruised volume in the Royal Gala Apples. Along with this linear relationship, immersing the apples in water for different amount of time thus increasing the turgor pressure in the apples will likely to result in a decreased bruise volume in the Gala apples.

Methodology

1. Materials

Selection of Apple

The research project was carried out in the Spring of 2015. The apple variety, Royal Gala, was selected due to its availability and popularity in North American markets. The BC-grown Royal Gala Apples were bought from the Save-On-Foods supermarket in Wesbrook Village on February 12, 2015. The masses of the Gala apples were chosen to be between 190-210 g to control the potential energy that will be applied to the apples. The apples with similar radius of curvature were selected to maintain the consistency of contact area. After the Gala apples were purchased, they were stored in the refrigerator between -1 and 1°C, which is the best range of temperature to maintain their firmness, and to prevent bruising due to decreases in humidity. Apples were placed at room temperature around 25 degrees Celsius for 24 hours prior to each experiment.
Techniques and Trials Conducted

Apples were dropped from 25 cm, and the dropping height was decreased by 2 cm per trial. This resulted 13 trials in total. Two replicates were used for each trial, thus 26 measurements were taken for each set of the experiment. Five measurements were made on each apple, and six apples were required for each set of the experiment. Three sets of experiments were performed in this research project. The first set was taken directly after the apples were placed in room temperature of 25 degree Celsius, whereas the other two sets of experiments were performed after immersing the apples into room temperature water (25 °C) for 1 hour and 18 hours, respectively. In the end, 19 Royal Gala apples in total were used for this research project.

Experimental Set-Up

The pendulum test was performed in all three experiments to increase the accuracy of the bounce back velocities of the apples (Bollen et al. 2001). A paper protractor and a 25 cm long string were attached to the wall using duct tape in order to control the drop angle for each sample (Figure 1). A metal rod was used to penetrate the apple from top to bottom in the middle to fix the apple in place. The other end of the metal rod is attached to a paper clip which is then attached to the string by duct tape. The apple was attached to the string and brought to different angles calculated with respect to the drop height (25 cm, 23 cm, 21 cm... etc). Flours were constantly put on the wall to mark the exact impact position on the apple and a colored marker was used to mark each impact position with numbers on the surface of the apples. This also made it easier to cut the apples in the middle of the impact area after 24 hours for volume estimation.

The motion of the apple was recorded using a video camera (Sony Cyber Shot DSC-TX1 with 10.2 megapixels) for further analysis. The instantaneous rebound velocities of the apples were measured using the LoggerPro program. The principle of conservation of energy was used to calculate the impact energy for each trial. The potential energy of the apple transforms into impact energy and kinetic energy when it reaches its lowest point on the pendulum. An assumption was made that negligible energy is lost to the surroundings and all energy lost is transferred as impact energy to the apples. The impact energy was calculated by:

Impact energy \((J) = \text{Potential energy (J) - Kinetic energy when the apple first bounced back (J)}\)

\[ E_i = mgh - \frac{1}{2}mv^2 \]

\(m\) is the apple mass (kg); \(g\) is the gravitational constant \((\frac{m_s}{s^2})\); \(h\) is the height of the apple (m); \(v\) is the rebound velocity (m/s).

![Figure 1. The pendulum apparatus. L is the length of the string, and Θ is the dropping angle. Apples were dropped by monitoring the drop angle Θ between the protractor and the string. Dropping height = cos(Θ) × L.](image-url)
After the pendulum drop test, the impacted apples were set at rest at room temperature for 18 hours, such that they could react with air. The reaction with oxygen led to oxidation and discoloration of the tissues. Apple bruise volume was measured using the Bruise Thickness Method devised by Mohsenin (1986). A crisscross cut was made on the bruised volume to get the two widths and depths of the bruised volume (Figure 2). ImageJ, a computer program for accurate measurement, was used to measure the lengths, widths and depths of each bruised volume. The formula devised by Mohsenin to calculate the bruised volume is:

\[ V = \frac{\pi (d_{avg})(3w_1w_2^2+4(d_{avg})^2)}{24} \]

\( d_{avg} \) is the average depth (m); \( w_1 \) and \( w_2 \) (m) are the widths of the bruise volume.

Results

Figure 3 showed the bruise susceptibility of apple in each set of experiment. It also showed the correlation between apple bruise and impact energy, as well as the effect of immersing apples into water for different periods of time. The bruise susceptibility or resistance of the Gala apple is the ratio of bruise volume and impact energy (Holt and Schoorl 1977) (Figure 3). The first set of experiment (apples without water bath) and the second set of experiment (apples with water bath for 1 hour) were not statistically significant because of their overlap between the 95 percent confidence interval. On the other hand, the first and second experiments had a significant statistical difference in bruise susceptibility with the third experiment (apples with water bath for 18 hours) since the 95% confidence interval of experiment three does not overlap with the first and second trial.
Figure 3. The bruise susceptibility or bruise resistance of Gala apples in three trials. Trial 1 (place apples at room temperature for 24 hours) has a bruise susceptibility of $6.68 \pm 2.75 \, \text{cm}^3/\text{J}$, Trial 2 (immersed apple in the water for 1 hour) has a bruise susceptibility of $5.63 \pm 1.78 \, \text{cm}^3/\text{J}$, and Trial 3 (immersed apple in water for 18 hours) has a bruise susceptibility of $2.31 \pm 1.07 \, \text{cm}^3/\text{J}$. The uncertainty is obtained from the standard deviation of the susceptibility at each height level.

Graphs for the Relationship between Bruise Volume and Impact Energy of apples in normal condition, immersed in water for 1 hour and immersed in water for 18 hours:

Figure 4. The apple bruise volume resulted from different impact energy(Experiment 1). The Gala apples stopped bruising when the impact energy is lower than 0.087J, thus the last 2 data points were not presented on the graph. The uncertainty of the bruise volume and impact energy was determined by the 95% confidence interval.
Figure 5. The apple bruise volume resulted from different impact energy (Experiment 2). The coefficient of determination has increased by 0.13 compared to the first set of experiment, which means experiment 2’s model fits better than experiment 1’s model. A few data points have large uncertainty of bruise volume, which is likely due to the errors that were resulted from bruise cutting procedures, as well as bruise volume estimation.
Figure 6. The apple bruise volume resulted from different impact energy (Experiment 3). The coefficient of determination has increased to 0.96 after the apples have water bathed for 18 hours, which means as the uniformity of the apple increases, the bruise volume of an apple can be better represented by a model. The last data point of this graph has a large uncertainty in bruise volume, this may due to most of the impact energy has destroyed the texture of the apple and resulted cracking on the surface of the apple, thus only a small portion of the impact energy led to bruising, so the variance is large between 2 replicates.

All three experiments show a positive exponential relationship between apple bruise volume and impact energy. Apple bruising threshold is the maximum impact energy that results no bruise on the apples. The Gala apples in Experiment 1 have the highest extrapolated bruise volume (5.00 cm$^3$) at the highest impact energy (0.48J), experiment 2 (3.39 cm$^3$) and experiment 3 (1.54 cm$^3$) follow after.

The trend of each experiment was modeled by using least squares fitting. In experiment 1 (apples without water bath), the exponentially increasing trend was modeled by: $y = 0.31e^{5.78x}$ with a coefficient of determination or $R^2$ of 0.72, which indicated that this was not a well-fit statistical model (Figure 4). In contrast, experiment 2 (apples immersed in water bath for 1 hour) produced a model that has a higher $R^2$ than experiment 1, at about 0.84 (Figure 5). Moreover, experiment 3 (apples with water bath for 18 hours) produced an even better model, with an $R^2$ of 0.96, which meant that experiment 3 has the best fitting model over all three sets of experiments.
These three models are directly compared in Figure 7, where they were represented as log-linear functions.

![Figure 7. Model comparison for bruise volume by time immersed in tap water (Experiments 1-3)](image)

The three models, separated by hours immersed in tap water, are directly compared in this semi-log plot. A trend can be observed in the decreasing susceptibility of apples to bruising with increasing immersion time.

**Discussion**

Due to the economic impact of apple bruising in the agricultural industry, bruise susceptibility is of great interest to farmers, distributors, and retailers alike. Bruise susceptibility is a measurement of how easily the apples may bruise from either intrinsic or environmental factors. A higher susceptibility value indicates an easier-to-bruise fruit texture that could be resulted from temperature, stiffness of the fruit (Abedi 2014), as well as the seasonal variation of the harvest (Bollen 2005). In this study, bruise susceptibility showed a dose-dependent reduction across three experiments with increasing time immersed in tap water. Apples without water immersion had the greatest susceptibility to impact (6.68 ± 2.75 cm$^3$/J), apples immersed for 1 hour had a decreased susceptibility of (5.63 ± 1.78 cm$^3$/J) although these differences were not significant, and apples immersed for 18 hours demonstrated clearly decreased susceptibility to bruising compared to the two models before (2.31 ± 1.07 cm$^3$/J). The trends observed for decreased bruise susceptibility in the apples is consistent with the biological explanation that increasing immersion time may be driven by increased cellular turgor pressure.

All three experiments show a similar threshold impact energy of around 0.08 Joules. This suggests that the tissues in the Gala apple must have a maximum resistance to outside force. The
constant threshold in all three sets of experiment is reasonable because it implies that cells within the apple can only resist a certain amount of energy until bonds within the molecules are broken by outside forces, regardless of what their turgor pressure may be.

In the three sets of experiments (Figures 4, 5, 6) with varied turgor pressure in apples, all three exhibit an exponential relationship between the bruised volume and impact (absorbed) energy. However, the coefficient of determination is the highest for the apples that have the highest turgor pressure, which is $R^2 = 0.9576$, and lowest for apples that were not immersed in water at all, which is $R^2 = 0.7194$. The experiment where the apples were immersed in water for 1 hour has an $R^2 = 0.8472$. These coefficient of determination values showed that the increase in the accuracy of the model as the turgor pressure increased may also be caused by the uniformity of apple in the second and third sets of experiments as immersing apples in water would decrease the variation in the turgor pressure of cells in the apple as well.

Gonzalez (2009) suggested that the intercellular space between the cells of the apples play a significant role in the amount of tissue bruising in apple. His investigation on the mechanism of bruising of the apple led to his conclusion that the more intercellular spaces, or air spaces, in apple tissues, the more tissue damage will occur. This research project used several sets of experiments to prove Gonzalez’s theoretical mechanism, such that as the apples were immersed into the water, apple cells absorbed the water into their vacuoles, which increased their relative cell size and decreased the air space between the cells. As a result, apples that were immersed into the water for the longest period of time had the smallest bruise volume across all of the impact energies compared to the apples that were immersed into the water for a short period of time and the apples that went without a water bath.

The apple bruise volume in relation with impact energy was modeled by bruise estimation models in Zarifneshat et al.’s study (2012). Zarifneshat et al. (2012) used impact force and energy as the independent values, and fruit properties, such as curvature radius, temperature and stiffness as constants. In this study, a model of the apple bruise volume as a function of impact energy was created. The model of apple bruising volumes with respect to the impact energy for the Gala apples in normal condition is $V = 0.31 e^{5.78E}$, where $V$ is the bruise volume, and $E_i$ is the impact energy of each mechanical damage. The models of the apple bruising volume are $V = 0.25 e^{5.95E}$ and $V = 0.15 e^{4.75E}$ for apples that were immersed into the water for 1 hour and 18 hours, respectively. By using these models, apple bruise volumes could be determined with consideration of the coefficient of determination mentioned above.

Since there were not many studies done on the bruising of the BC Royal Galas, this research is a pilot study in investigating the bruising properties and its relation to the impact energy and turgor pressure in the Gala apples. One of the most interesting trends in this experiment is the effect of turgor pressure on the bruising volume of the BC Royal Galas as the experiment showed that as the Gala apples gain more turgor pressure by being placed in a
hypotonic water bath, the bruise susceptibility decreased significantly compared to the apples that were impacted under normal conditions.

Evaluation of Errors

Both random errors and systematic errors are present in this study. Random error include measurement errors during the measurement of the apple bruise dimensions using the ImageJ program. Although ImageJ is a fairly accurate program for measuring, it is also subject to a small amount of random errors since the measurements are done manually. Random errors also occur in the measurement of instantaneous rebound velocity using the LoggerPro software. Due to the limited accessibility to more accurate video recording devices, the instantaneous velocity graph is subject to random error due to the uncertainty created by the blurred images when the velocity was too high. Furthermore, due to the limited access to better equipment, the mass of the apples were only measured to the precision of ±1 grams. The uncertainty for the mass of apples is ±0.5 grams. Systematic errors are errors that exist within the experimental procedure. For instance, after the apple rebounded, it had to be caught by hand to prevent a second impact. However, the act of catching it may also result in an additional second impact on the apple, which may have contributed to larger bruise volumes and variance in the data. A soft material could be used to catch the apple next time to decrease the risk of unintended mechanical damage.

Improvements

There are many improvements that can be done to the experiments for a more comprehensive data set. First of all, there could be more sample points for each experiment. For this experiment, we used a total of thirteen samples ranging from 0.25 meters to 0.01 meters in dropping height. More samples in between each sample point and possibly going above 0.25 meters would be useful in making a better model. In addition to this, adding more trials per sample can be a good strategy to reduce the standard deviation of the volumes calculated and provide more confidence to the model. Another improvement could be using more precise devices, such as a better weighing balance, a more accurate experimental set up, and a camera with more frames per second. Lastly, more sets of experiment that varies the amount of water bath immersion time can be conducted to find out whether a model could be devised for the bruise susceptibility of the Gala apples with regard to the amount of time they are immersed in water baths.

Future Studies

Future studies should aim to replicate the experiments conducted in this current study using different immersion times. This would help them to find the optimal immersion time for Gala apples to decrease bruise susceptibility due to impact energy. It may also be useful for future studies to include the effect of temperature on bruise susceptibility. Finally, the end-goal should be to generate a detailed predictive model for the bruise susceptibility of Royal Gala
apples that incorporates all of these environmental exposures into a single unified model. Once this has been accomplished, similar studies could be conducted on other popular apples.

Conclusion

BC-grown Royal Gala Apples have a bruise threshold impact energy of 0.08 J which is independent of time immersed in tap water. Furthermore, the relationship between bruise volume and impact energy was explored, arriving at three models for apples without water bath, with 1 hour of water bath, and with 18 hours of water bath respectively: $V = 0.3052e^{5.7812E}$, $V = 0.2532e^{5.9451E}$, and $V = 0.1492e^{4.7497E}$. While all three models found bruise volume to be dependent upon impact energy, apples with 18 hours of water bath were observed to have significantly decreased bruise susceptibility. The findings of this study can be applied to the transportation of apples, which would minimize economic and environmental waste attributed to the disposing of bruised apples. Future studies should analyze the potential economic impact of water immersion practices for apple transportation, and determine the optimal immersion time to decrease bruise susceptibility.

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Literature Cited


