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Design of thermoformed plastic container using mould from three-dimensional printing for pear protective performance

ABSTRACT

Thermoforming is a widely used plastic packaging method due to its affordability, high protective performance, and ability to prevent mechanical damage to fruits during transportation. This study aimed to investigate the factors influencing the thermoforming packaging moulding process, evaluate the structural strength of thermoformed packaging, and assess the effectiveness of various shaped thermoformed containers in protecting pears. The prototype design was based on different geometric shapes and dimensions, divided into four relief geometries: cylindrical (M1), semi-circular (M2), geodesic dome (M3), square (M4), and commercial dome shapes. According to the mould thermoforming process, the mockups of each pattern were modelled using SolidWorks software and formed using a 3D printer. Polyvinyl chloride (PVC) plastic sheets were formed in a container mould with a thermoformed machine under the same parameter conditions of time, temperature, and pressure. The compression resistance of the thermoformed containers was tested. According to these findings, the compression force was higher in inferior thermoformed containers than in superior thermoformed containers. This is due to the relief size, geometry, and dimensions of the thermoformed containers. Then, thermoformed containers were employed to perform the dart drop impact test, with the pears dropped from heights of 20, 40, and 60 cm. The thermoformed container sample with a square shape (M4) had the lowest proportion of bruises (8.33%) on fruit. For container sample M4, the bruised area (BA) was assessed at drop heights of 20, 40, and 60 cm at 97.12, 140.75, and 206.02 square millimeters, respectively. Based on this finding, the bruise volume increased as the impact height increased. Additionally, a drop test was performed at a height of 90 cm using a thermoformed container with pears in a double-wall corrugated board for the BC flute. A higher total area of bruises on pears without thermoformed containers was observed in the evaluation of bruised damage. Therefore, this study concludes that the shape, size, and relief position of thermoformed containers reduce the damage caused by the compression strength and dropping height during transportation.

KEY WORDS

three-dimension printing, thermoforming container, packaging design

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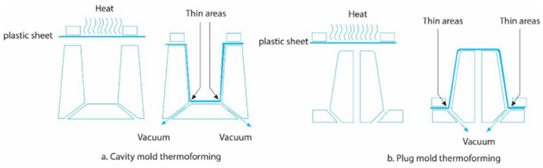
Introduction

The current retail packaging design for fruit containers in the postharvest industries involves thermoforming packaging. The plastic thermoforming technology is highly popular in the packaging industry due to its cost- effectiveness, ease of production, and rapid processing capabilities. It's particularly advantageous for retailing fresh fruits, as it helps protect the product during transit and preserves long-term quality. Fresh fruits, both domestically produced and imported, especially those with delicate textures, are susceptible to damage during transportation. Soft fruits can easily develop bruises, making them more prone to microbial degradation. In addition, the aforementioned characteristics of plastic thermoforming packaging is available options for protecting the quality of delicate fruits. In previous research, soft fruits such as kiwi, peach, and cantaloupe were been used for experimentation of packaging protection for transport (Xia et al., 2020; Lin et al., 2020; Günther et al., 2021; Azam, Saad & Amer, 2022).

Apart from the protective role of packaging, the types of packaging material are crucial in preventing fruit damage. PVC and PET are mostly chosen to create the thermoforming packaging in industry because their properties can form easily, durable structure of preventing impact and clear surface. Three-dimension mould in this study not only did the researchers utilize thermoforming technology, but they also explored the design of containers for fresh produce. They analyzed the dimensions of the containers using SolidWorks software and three-dimensional printing systems. The design factors, such as curved shapes, triangular shapes, and the creation of ribs, contributed to the efficiency of protecting the packaged fruits. Additionally, the study included testing the structural strength of the thermoformed plastic container and its effectiveness in reducing damage during transportation in comparison to foam boxes, plastic crates, and paper pulp boxes when fruits were stacked.

Selke & Culter (2016) described the procedures of forming thermoformed packaging using plastic sheet. The thermoforming process has three basic steps: heating the sheet, forming the sheet, and trimming the part. There are many methods for moulding the sheet of plastic, once it has been softened by heat. The simplest are drape forming, vacuum forming, and pressure forming. The normal procedure is to make a prototype mould to determine the process parameter of product geometry. Prototype molds can be made by various techniques. Robertson (2013) presented the description of a plastic sheet (generally 72-250 mm thick) of thermoplastic material is heated to its softening temperature, usually by means of an infrared radiant panel heater. By either pneumatic or mechanical means, the sheet is forced against the mould contours and, after cooling, is removed and trimmed.

Typical thermoplastics used for thermoforming include HIPS, PVC, PP and PA. Soroka (2009) revealed the thermoforming methods is the simplest thermoforming method. The core part of the die simply pushes the softened plastic into the matching cavity half. Most thermoplastic materials can be thermoformed, including single-polymer materials, co-extrusion and laminated sheets. Pliable plastic sheet can be formed by mechanical means, with vacuums, with pressure or by combinations of these. In Figure 1 exhibits vacuum holds are required in the cavity' s lowest point. The most common application of thermoforms is for various forms of blister or clamshell display packaging (Soroka, 2009).



» **Figure 1:** *Simple vacuum forming over cavity (a) and plug mould (b) the material is pulled to the mould shape when a vacuum is applied between the mould and sheet interfaces*

According to research in the area of 3D modeling, Chantarapanich et al. (2020) designed plastic tray models using computer-aided design (CAD) and three-dimensional printing. The 3D models were then evaluated for the compression strength of the tray geometry using finite element (FE) method analysis. They found that the bottom corners of the tray exhibited a high-stress magnitude. Based on the FE results, the edges, shape, and plastic sheet thickness provided sufficient strength to withstand the vertical stacking compression of the thermoformed tray design.

Nilmanee (2023) designed packaging assistant opener tools to improve consumer access to contents by creating models with SolidWorks software and prototyping them using a 3D printer. The FSUDE system was employed to evaluate the function, safety, usability, design, and engineering of all prototypes.

Based on the results of this study, form, dimensions, surface texture, friction, and grip posture were factors affecting torque force exertion, slitting and cutting force, and the openability for consumers.

Ibrahim & Fahmy (2021) developed an attractive, eco-friendly packaging item using polylactic acid (PLA) filament and considered health impacts through the structural design of a 3D-printed bottle prototype. Their study aimed to apply ergonomic principles to design a comfortable packaging bottle that is easy to drink from and handle. Tuhin et al. (2021) studied the features of an opioid smart packaging system that includes a dual-wall medical bottle for anti-tampering performance testing.

The inner and outer containers were designed using SolidWorks and 3D-printed with corresponding materials: the inner container was made from polylactic acid (PLA) filament, while the outer container was made from acrylonitrile butadiene styrene (ABS) filament. They varied in wall thickness, the gap distance between the walls of the inner and outer containers, and channel widths.

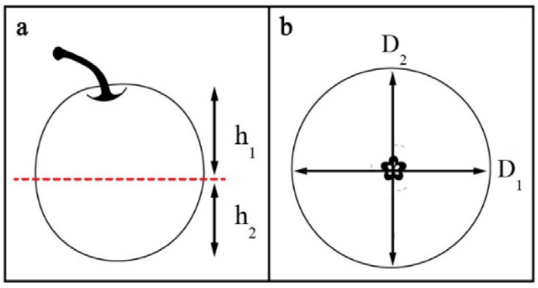
In this research, celery was chosen as the focus due to its delicate nature, susceptibility to bruising, relatively high market value, and the need for a packaging material with a strong structure capable of providing protection against external impacts. The study used three-dimensional design software to enhance the efficiency of the packaging in protecting celery quality. The research also examined the damage incurred during mechanical testing, including how shape characteristics influenced the structural strength and the packaging's ability to reduce impact forces. The shape, size, and relief position of thermoformed containers play a significant role in reducing damage from compression and drop height during transportation. Therefore, the objectives of this study were to investigate the factors affecting the plastic thermoforming packaging process for pears and to evaluate the structural strength of the thermoformed packaging. Additionally, the effectiveness of thermoformed packaging in various shapes for protecting pears was assessed.

Materials and Methods

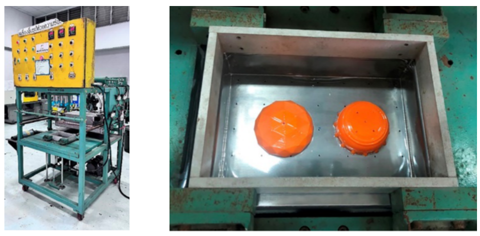
Thermoforming design process

The first process was designed for the mockup samples of thermoforming container molds using SolidWorks software Version 2021. According to the mold design, the average pear dimension was measured by collecting fresh pears in supermarkets in Thailand. Figure 2 presents the technique of measuring the ratio dimension within two parts: the superior mold (h_1 and h_2) and inferior mold (D_1 and D_2) (Rodríguez-Parada, Mayuet & Gamez, 2019a). The mold for the pear was created using four different conceptual forms, including a control mold based on the commercial type. Next, the mockup files were converted from Standard Triangle Language (STL) format to G-Code format using ideaMaker software. Each mockups pattern was modeled and formed using a 3D printer (Pro 2Plus, Ruise 3D printer, United States) with 1.75 mm diameters ABS filament (Acrylonitrile Butadiene Styrene) set at a printing temperature of 245- 265 °C. For the thermoforming process, the printed mold samples were placed in the box of the thermoforming machine, as shown in Figure 3.

Based on the plastic sheet formation, a polyvinyl chloride (PVC) plastic sheet was selected to form the samples of the thermoforming process with the machine. The melting temperature (Tm) of the PVC sheet was measured using DCS (differential scanning calorimetry (DSC, Mettler DSC 30, USA) in accordance with ASTM 3418-08. PCV samples of approximately 3-5 mg were weighed and sealed in aluminum pans, using an empty sample pan as a reference. The heating scan was performed from 35 °C to 270 °C. The heating rate was increased at a rate of 10 °C/min. A thermal analysis technique for the heat flow into or out of a sample can be measured as a function of temperature and time control in the thermoforming process. PVC sheets were clamped in the thermoforming machine and heated to 210 °C for 40 s under a pressure of 4-5 bar and vacuum of 30 inHg. Five configurations of the top and bottom molds were formed using a thermoforming machine, and all tests were conducted under the same conditions.



» **Figure 2:** *Model of result measurement of pear samples (a) the superior and interior heights (b) the diameter of the pear*



(a) (b)

» **Figure 3:** *Thermoforming design process (a) Thermoforming machine (b) model features after forming*

Process of compression testing the thermoforming samples

The compression resistance force of the thermoforming plastic sheets for each model was measured using a universal testing machine (H10KS, Tinius Olsen, Taiwan) on the upper and lower parts of each model. Five different mold geometries were tested with five repetitions for each model. During the compression force test, the thermoformed samples were placed securely on the grips of the machine. The load cell was set to 50kN, and the compression speed was set to 10 mm/min (Rodíguez-Parada, Mayuet & Gamez, 2019b). The samples were compressed from above, as shown in Figure 4.

» **Figure 4:** *Compression test with Universal testing machine*

Bruise size measurement of pear fruits using dart drop impact and drop testing

After molding the thermoforming samples of various calibres, they were tested with a dart drop using a Dart drop impact tester (Model DDI, ATLAS, United States). Pear fruits were individually packed in thermoforming containers of different forms and subjected to drop tests, as described by Pathare & Al-Dairi (2021). Each pear-containing container was evaluated for its protective performance by testing drop heights of 20, 40, and 60 cm, with three pears tested at each height using a 260-gram pendulum (Figure 5). After the drop tests, the pears were stored at room temperature for two days, after which the bruise size of each pear was measured. Follows (Equation 1): where mb is the mass of dropped ball 260 g, g is the gravitational constant (9.81 m s-2), and h is the drop height in meter. (Pathare & Al-Dairi, 2021). Table 1 lists the impact energy generated from the various drop impacts.

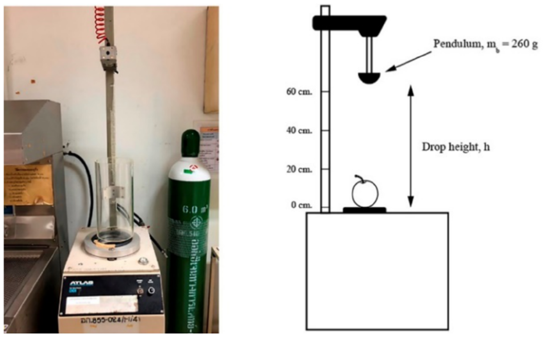
$$E_i = m_b \times g \times h \text{ (J)} \quad (1)$$

Each shape of the samples was 3 tested repetitions. The pears were plated at room temperature for 2 days. On the second day, the tested pears were peeled and measured the bruising diameter (W1 and W2) and the depth as shown in Figure 6. The weight loss percentage (% weight loss) was calculated using Equation (2) while bruise area and internal bruise index percentage were calculated using Equation (3) and Equation (4), respectively. The physical characteristics of the thermoformed container were observed and recorded the results.

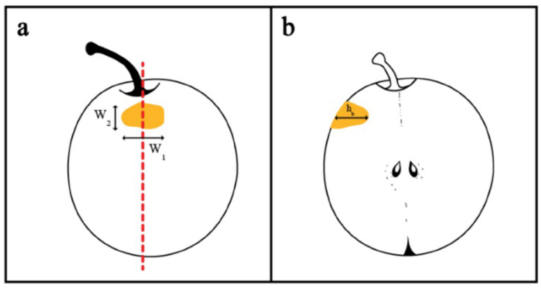
$$\text{Weight loss} = (M_0 - M_n) / M_0 \times 100\% \quad (2)$$

$$\text{Bruise area (BA)} = (\pi/4) \times W_1W_2 \text{ (mm}^2\text{)} \quad (3)$$

$$\text{Bruise index (BI)} = \frac{\Sigma(\text{bruise scale} \times \text{number of fruits corresponding the scale})}{\text{total fruit number} \times \text{highest number of bruise scale}} \times 100\% \quad (4)$$



» **Figure 5:** *Experimental set up of Dart Drop Impact Tester*



» **Figure 6:** *Bruise measurements (a) bruise diameter and (b) bruise depth (Pathare & Al-Dairi, 2021)*

Table 1

Drop height and impact energy produced in the experiment

Drop height (cm)	Impact energy (J)
20	0.510
40	1.020
60	1.530

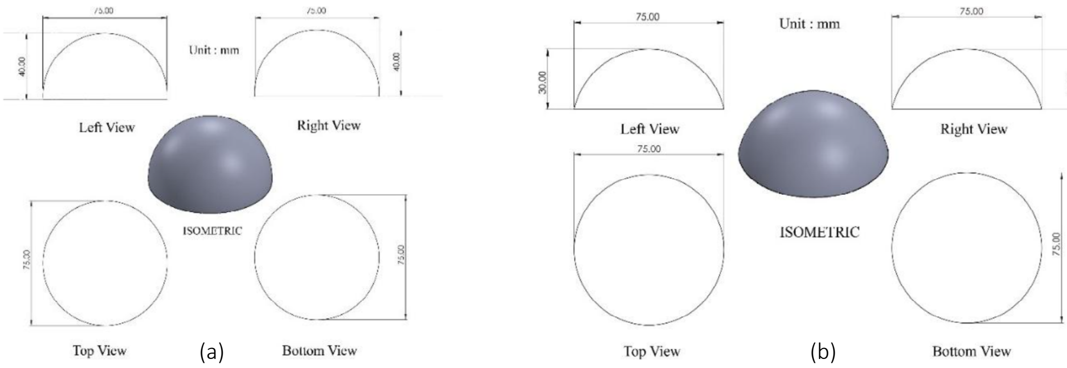
Furthermore, this study also tested the protective efficiency of fresh pears contained in thermoforming samples using drop testing. The pears were packed in thermoformed plastic containers of five different geometries and then fixedly placed in the corrugated boxes commonly used in commercial transportation as regular slotted containers (RSC) by the private logistics company (Figure 7). The dimensions of the box were 27 × 37 × 14 cm. Pears were observed and recorded after the test. Drop resistance testing was performed using a drop test machine model GT-7003, and the drop height was set at 0.90 meters (Xia et al., 2020). The pears were kept at ambient temperature for two days. On the second day, the pears were peeled, and bruising of the pears was inspected.

» **Figure 7:** *Drop testing machine GT-7003, GOTECH, Taiwan*

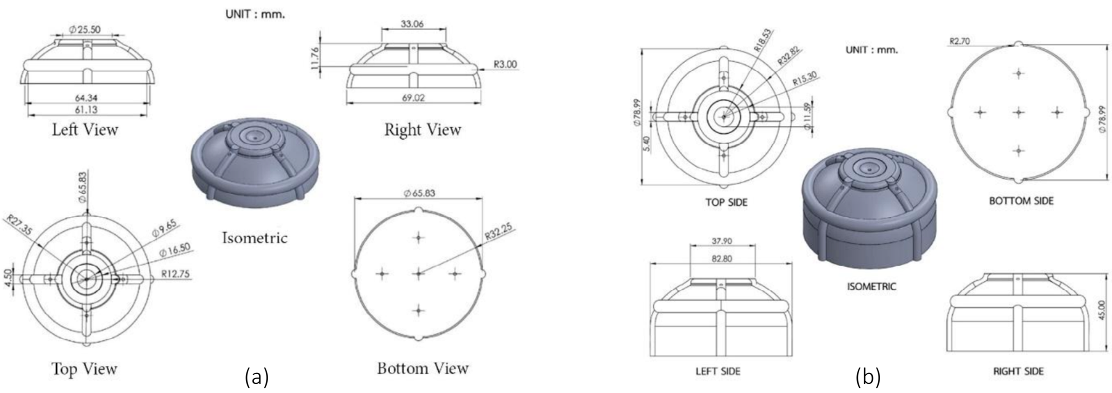
Results and Discussion

Conceptual design of thermoforming mould

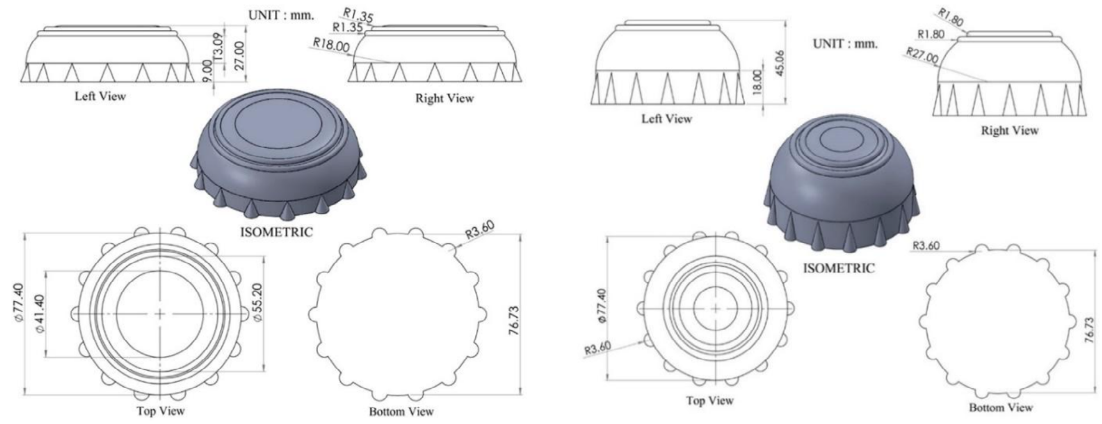
The concept of thermoforming mould design was started with measuring the shapes and dimension of fresh pears from the supermarkets. According to the mould mockup design, the mold's geometry of was divided into 2 parts in different sizes: a superior and an inferior component. The superior mould part was taller than inferior part because both parts had distinct roles in protecting the fresh pears. The inferior based mould was responsible for supporting and reducing impact forces. On the other hand, the superior component of the mould was designed to assist pressure occurrent from stacking the pears in packaging during transportation. It was also facilitated easy opening and ensured proper interaction between the supporting base and the cover lid. Furthermore, the design concept also considered the efficiency in pressure resistance. This study involved defining the dimensions for both small and large relief shapes including rectangular and triangular forms. The orientation of these shapes is also examined in both vertical and horizontal directions to enhance structural integrity, ensuring the can withstand pressure and absorb impacts effectively. The mould mockup samples were created five geometries using SolidWorks in drawing, as shown in Figures 8 to 12.



» **Figure 8:** *Drawing of the mould dimension used for thermoformed commercial type (a) superior mould (b) inferior mould*

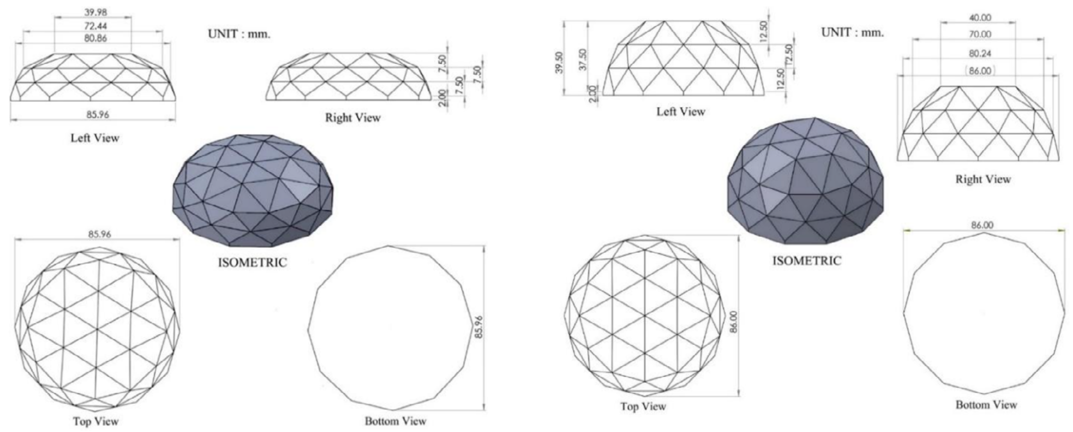


» **Figure 8:** *Drawing of the mould dimension used for thermoformed container type M1 (a) superior mould (b) inferior mould*



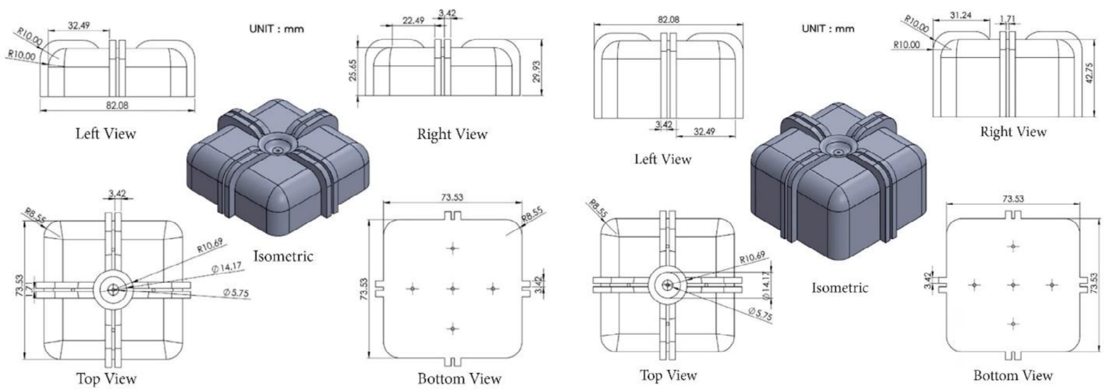
(a) (b)

» **Figure 10:** *Drawing of the mould dimension used for thermoformed container type M2 (a) superior mould (b) inferior mould*



(a) (b)

» **Figure 11:** *Drawing of the mould dimension used for thermoformed container type M3 (a) superior mould (b) inferior mould*



(a) (b)

» **Figure 12:** *Drawing of the mould dimensions used for thermoformed container type M4 (a) superior mould, (b) inferior mould*

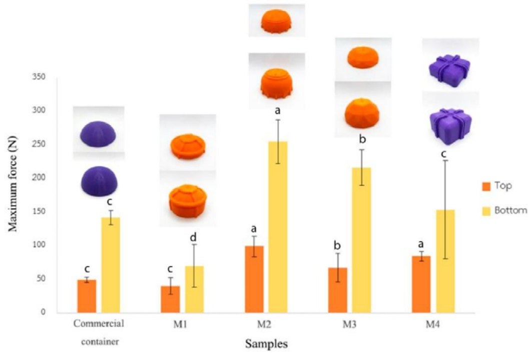
Strength elevation of thermoformed mould structure

Figure 13 depicts the compressive resistance force of thermoformed plastic containers using five structural geometries. The container sample Model 2 (M2) showed a greater compressive resistance force than the other samples. The superior mold section had a higher compressive force than the inferior mold part, with values of 254.67 Newtons and 99.40 Newtons respectively. In contrast, the sample M1 in cylindrical shape was the lowest compressive strength to compare with different geometries under 40.47 Newtons for superior parts and 70.37 Newtons for inferior parts. This finding was consistent with previous study by Rodríguez-Parada, Mayuet & Gamez (2019b) which confirmed that their experiment consistently showed higher compressive resistance in the inferior mould part compared to the base across all moulds, attributed to the smaller size of the mold resulting in reduced compressive strength. The findings of Afshariantorghabeh, Kırki, & Leminen (2022) indicated that the geometric shapes, thickness, and low mold depths of thermoforming affected the distribution behaviour and mechanical properties. In addition, when comparison of geometry M2 with the other geometries had lower compressive strength due to enhancement of force distribution and resistance for curved side shape mould. However, the force distribution capability of mould design for thermoforming process in this study was depended on mould dimension, geometry, thickness, relief features, and relief position.

Table 2 illustrates deformation of the computer simulation and the actual testing of the molded prototypes with different geometries using compression force 50 Newtons. The results found that the thermoforming mould samples had the same deformation as the actual samples and computer simulation testing. According the results of resistant force and color appearance on the samples during both tests, the red areas are indicated region of maximum damage and deformation configuration under applied force, while the blue areas are indicated the strongest or without deformation boundary. Furthermore, the results of both tests were consistently related with each other as visual simulation and laboratory evaluation.

Effect of thermoformed containers on bruise area and bruise index in protecting pears

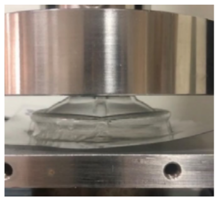
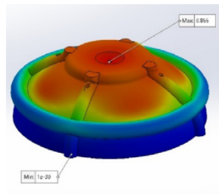
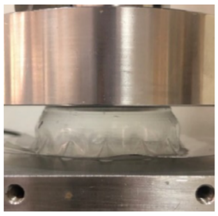
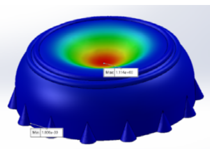
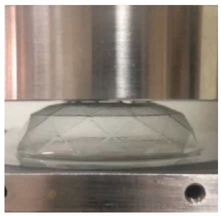
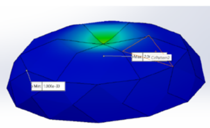
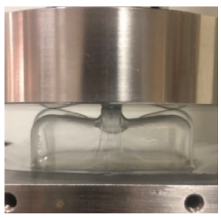
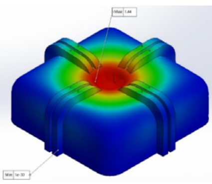
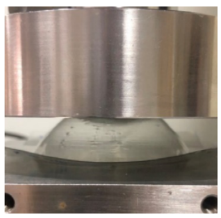
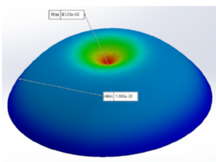
The result of bruising area with fresh pear by conducting the dart dropping impact test, as shown in Figure 14. A 260-gram pendulum was dropped in heights of 20, 40, and 60 centimeters on the pears. All the pears were packed inside each thermoformed sample of different geometries. It found that the trend of bruising area was increased with higher drop heights.



» **Figure 13:** *Maximum compression force of thermoformed plastic samples with varying geometries, mean value followed by different superscript indicates the significant different (p < 0.05)*

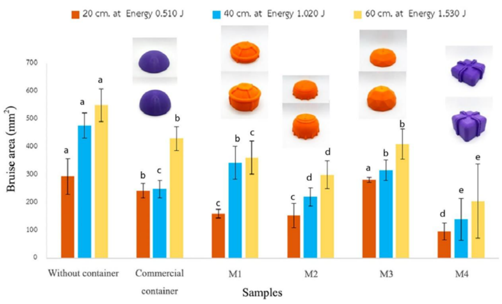
Table 2

Comparative analysis of compression resistance and compression testing simulation

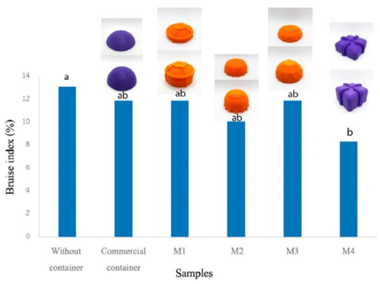
Samples	Compression testing in the experiment	Simulation of compression test
M1		
M2		
M3		
M4		
Control		

The rectangular-shaped container (M4) was the most effective in protecting the pear, with a bruising area of 97.12, 140.75, and 206.02 square millimeters for drop heights of 20, 40, and 60 centimeters, respectively. Additionally, comparing the pear bruise area of a thermoformed sample without a container, and a commercial container shape was obviously higher than the other container geometries. According to the similarity of the studies by Pathare & Al-Dairi (2021) with pears and Azam, Saad & Amer (2022) with cantaloup, they confirmed that the results found a similar trend of increased bruising area with higher drop heights testing. According to study of Lin et al. (2020), they investigated the effect of cushioning materials on quality damage of peaches in the vibration test. The bruise area of peaches was reduced to involve with types of cushioning material for protective performance.

Accordance with the experimental results of the bruising index for packed pears in thermoformed containers, the rectangular-shaped sample (M4) had the lowest bruising index of all the container sample forms at 8.33%. On the other hand, pears packaged in commercial dome-shaped containers had the highest bruise index (11.9%). The indication of the rectangular-shaped container (M4) had a lower bruising for pears was due to its different sizes and shapes of relief. The cause also provided a larger surface area to absorb force compared to other shapes, as shown in Figure 15.



» **Figure 14:** *Bruise area of pears under dart drop testing using different thermoformed shapes, mean value followed by different superscript indicates the significant different (p < 0.05)*

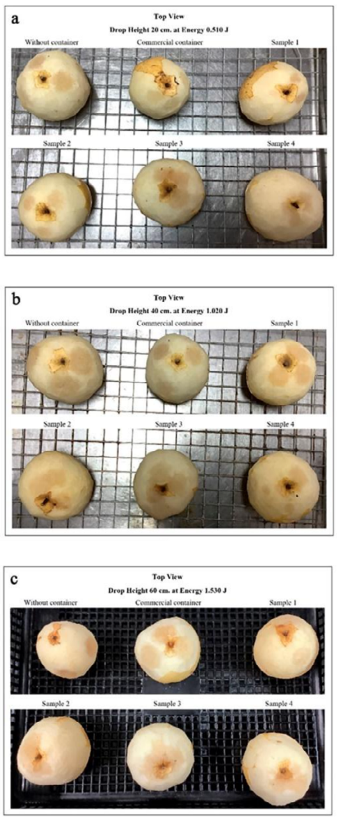


» **Figure 15:** *Bruise index of pears under dart drop testing using different thermoformed shapes, mean value followed by different superscript indicates the significant different (p < 0.05)*

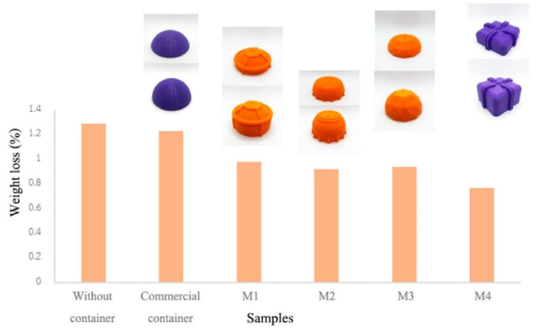
Evaluation of pear damage external appearance and weight loss

In Figure 16 illustrates the external characteristics of fresh pears during containing thermoformed containers to place on the corrugated box after drop tests at heights of 20, 40, and 60 centimeters for 2 days of storage at room temperature. High damage patterns on pear surfaces were observed in pears contained in dome-shaped container (commercial shaped sample) and without any container. Conversely, the bruise areas on pears stored in rectangular-shaped containers (M4) and small semi-circular-shaped sample containers were less noticeable compared to other container shapes. In terms of drop heights, the surface areas of the pears were highly damaged at a drop height of 60 centimeters. After drop tests, in Figure 17 presents the weight loss percentage of pears. It was found that pears were packed in commercial container had the highest weight loss percentage at 1.23% when compared to the other thermoformed container samples. Among these, the rectangular container (M4) had the lowest weight loss percentage at 0.77%.

The study of Xia et al. (2020) investigated the impact of three packaging materials (EPS box, wooden box, and HDPE box) on the lowest loss in kiwifruit during free drop test. The results indicated the potential of EPS box as softening and high young’ modulus material to reduce bruise damage and the lowest weight loss of kiwifruit.



» **Figure 16:** *External appearance of pears surface containing in thermoformed samples by drop testing*



» **Figure 17:** *Percent weight loss of pear storge*

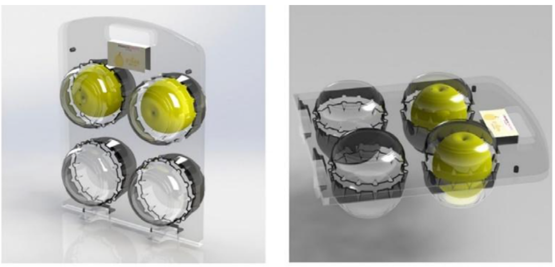
The development of thermoformed container prototypes for commercial applications

After developing the sample shapes of a thermoformed plastic container, they were evaluated based on tests for their ability to withstand compression, impact resistance, drop impact resistance, and the visibility of pear fruit during containment.

The researchers proceeded to the next phase of the study. They were modeled containers aimed at enhancing value and usability. Additionally, they designed labels to be attached to the mockup. The thermoformed plastic container sample utilized two shapes: a cylindrical shape with small relief (M2) as shown in Figure 18, and a rectangular shape (M4) as shown in Figure 19.

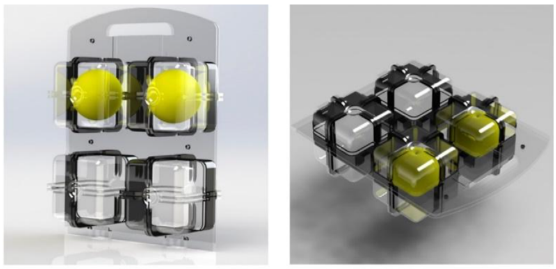
The design concept focused on creating packaging capable of accommodating all four pear fruits. The package mockup can be placed both vertically and horizontally in a stable orientation.

The interlock mechanism of the mockup was incorporated to ensure secure closure upon assembly, and convenient rectangular holes were included for easy handling.



(a) (b)

» **Figure 18:** *The mockup of thermoformed plastic container using SolidWorks with Semi-circular geometry (M2) in design display on the vertical (a) and horizontal (b) directions*



(a) (b)

» **Figure 19:** *The mockup of thermoformed plastic container using SolidWorks with Square geometry (M4) in the design display on the vertical (a) and horizontal (b) directions*

Conclusion

In designing molds, 3D printing is one of the choices for designers to improve primary mould prototypes. Innovative materials like ABS filament, with model forming, are useful for higher temperatures in thermoforming packaging. This study evaluated the structural integrity of various thermoformed container shapes and assessed their effectiveness in protecting pear fruits. Several key findings follow the effect of thermoforming design on success. Containers with superior mould parts exhibit greater resistance to compression than those with inferior mould parts. This is because the larger bottom sections can better withstand external forces. Impact tests conducted on plastic containers at varying heights revealed that, as the height increased, the incidence of bruising on pear fruit also increased significantly. Performance tests of thermoformed plastic containers showed that character container mould 4 (M4), with its rounded edges and rectangular shape, was the most effective in reducing bruise indices and bruised areas on pear fruit. Transport protection tests indicated that pear fruits packaged in thermoformed containers experienced significantly less bruising than those transported without packaging. In conclusion, this study emphasizes that the shape, dimension, and location of the relief of heat-formed plastic containers play a crucial role in minimizing the damage from compression and impact tests.

Ethical approval

This article dosed not contain any studies with human participants or animal performed by any of the authors.

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