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Packaging optimization for reducing bruising in pears

Asma Mecheter [*,a], Faris Tarlochan [b]

Department of Mechanical and Industrial Engineering, Qatar University, Doha P.O Box 2713, Qatar

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Abstract

Economics losses due to fresh produce damage is considered a serious issue in the agriculture industry. Fruits like pears are most susceptible to damage due to their soft and sensitive skin. In this study, rosemary pear 3D finite element (FE) model was established through 3D scanning and reverse engineering methods. Elastic-plastic material properties of pear including modulus of elasticity, density and bio-yield point were measured through mechanical compression test. The FE model was validated with physical bench experimental drop test. A mesh sensitivity analysis was performed in order to ensure optimal balance between results convergence and computational time. A polylactic acid (PLA)-based design structure was proposed in order to serve as a cushioning package for pears. This design has reduced bruising in pear by 65%. Design of experiments (DOE) was performed to investigate the influence of design process parameters in both responses bruising volume and structure internal energy. Response surface methodology results have revealed that circular thickness of structure is responsible for bruising volume. Thinner circular rings would result in minimized localized inner fruit stress. A moderate structural thickness is recommended to be adopted as thicker structures would result in higher internal energy which will be transferred to the fruit as bruising. The proposed design can be extended to be used as a multi cell packaging to accommodate multiple fruits in the same package ensuring the protection for each pear individually. The design can be recyclable, reused, and remanufactured as it is made from PLA. Design practical implications and supply chain insights were addressed along with future research directions. Fresh produce logistics and operations should consider the adoption of such packaging in order to minimize economic losses and extend shelf-life of fruits.

1. Introduction

Substantial economic losses happen in the agriculture industry due to fresh produce bruising. About 30% of fruits suffer from bruising problems in the post-harvest stage [1]. Bruising and mechanical damage usually happen due to several factors including impact, vibration, and puncture during the post-harvest supply chain. Fruit with soft texture such as pears are highly likely to get damaged making them particularly perishable and vulnerable during processing and handling operations. Bruising in fruits is defined as the subcutaneous tissue failure without skin rupture where affected areas will appear discolored [2]. Current practices investigate bruising related issues through laboratory test through various approaches. These approaches include pendulum test, spherical impactor test, x-ray and CT imaging, etc. Drop impact test is the most popular one among the mentioned tests [1]. Utilizing finite element analysis (FEA) to simulate the drop impact test for a wide variety of fruits assess in providing insights into bruising and damage characteristics. FEA enables the simulation of fruit drop impact at different predetermined heights, impact collision surfaces, angles and conditions[3]. Furthermore, FEA allows the analysis of energy distribution, stress distribution, damage and bruising prediction. Therefore, FEA tools can be

*Corresponding author: am1508546@qu.edu.qa
[a]orcid.org/0000-0002-1021-4462; [b]orcid.org/0000-0002-0405-145X
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leveraged in order to test different drop impact conditions for the pear utilizing cushioning packages.

Research on analyzing pear fruits response to collision is being done through hyperspectral imaging [4,5], X-ray and computed tomography [6], machine learning and soft computing methods[7,8] and by finite element analysis [9–13]. In this work, we have utilized finite element methods to test the pear drop and obtain bruising related data. Yet, the main purpose of this paper is not to only gain insights about fruit bruising but rather propose packaging solutions and cushioning design for pear packaging. Stropek et al. [14] have studied the relation between bruise susceptibility and internal energy with impact velocity of two pear cultivars namely 'Xenia' and 'Lukasowka'. The study has shown that internal damage energy and bruise susceptibility increase with the impact velocity. Also, energy dissipation mainly occurs during the initial impact stage. Yousefi et al. [13] have predicted the bruise damage in Natanz pear at three different ripeness levels, different platforms and impact angles. Authors have noticed that the maximum pear bruising happens when dropping the fruit at 90 degrees. This is because the weight force and falling path are in the same direction. It was found out that the maximum stress usually occurs in regions of minimum radius of curvature while minimum stress occurs at maximum radius curvature of pear. The bruise susceptibility of Ankara pear variety was investigated in Celik's study where it was found out that dropping the fruit on rubber-based platforms yields in the least bruising [10]. Li et al. [12] have mentioned that pressure area and average pressure are factors associated with severity of bruising. Authors have concluded that the total contact stress area distribution of pears is always larger than measured damage area.

Packaging is critical in the post-harvest operations of fresh produce, which serves as primary protection for fruits subject to different loading conditions. This is why studying the interaction between packaging and fresh produce is crucial in order to minimize bruising and maintain the high-quality fresh produce delivery to consumers [15]. The choice of packaging material is crucial to reduce probability of bruising in contact with the material [1]. Utilizing polyethylene-based partitions boards withing folding plastic baskets has proven its efficiency in reducing bruises in Hongmeiren oranges [16]. Foam net packaging for peaches has outperformed other materials like foam sheets, polypropylene trays, and corrugated fiberboard in terms of protective capacity, sustainability and economic impact [17]. However, foam and paper-based packages are more likely to absorb excessive amount of moisture which will limit their capacity for long-term storage [18]. Furthermore, foam packages may not offer the same level of protection, durability, and thermal stability in comparison to plastic-based packages, especially for highly sensitive fruits during rough handling conditions [19]. Studies have shown that foam material can result in more bruising to fruits. This is why, plastic is highly recommended to be used in fresh produce packaging, as it is impact-resistant, customizable, recyclable and reusable. Mecheter et al. [20] have suggested the use of recycled water bottles polyethylene terephthalate (PET) through a spiral design structure where bruising in pears was reduced by 50%. Current literature lack packaging designs made from biodegradable material to provide cushioning for pears in terms of long-term effectiveness and sustainability in reducing bruising. Therefore, more research is needed on plastic-based fruit packaging and customization of packaging designs which would provide holistic insights on fruit-packaging behavior [21]. This paper is trying to address the following question: How can design of cushioning packaging using 3D printed biodegradable materials, minimize bruising in pears ? The objective of this paper is to use reverse engineering and mechanical testing methods in order to test a real pear which will be later assessed with a pear physical model. Furthermore, we propose a polymer-based fruit packaging design that will provide cushioning for pears during transportation. Another objective of this paper is to investigate different geometric parameters and how they influence bruising in fruits through design of experiment and response surface methodology.

2. Materials and Methods

The methodology used in this paper follows a systematic approach, as outlined in the following sections.

2.1 Determination of Fruit Physical and Mechanical Properties

2.1.1 Reverse Engineering Modeling

Fresh pears Pyrus communis, variety "Rosemary" was purchased from the market and directly transported to the laboratory at Qatar University. The average weight of the sample was 128 ± 1.74 grams. The pear was 3D scanned with a lidar scanner through mobile phone application to capture the 3D point cloud of the pear surface. Blender software was used to remove the redundant points from the point cloud. MeshMixer software was used to build the fruit solid model out of the mesh model. The actual, mesh and solid models of the fruit are shown in Fig. 1. The 3D scanned fruit was cut into half where the length and width of the pear were measured by a vernier caliper. The length and width dimensions were also measured in SolidWorks as shown in Fig. 2. We can consider that the 3D scanning process was precise as the error for width and length dimensions 0.6% and 0.3% respectively.

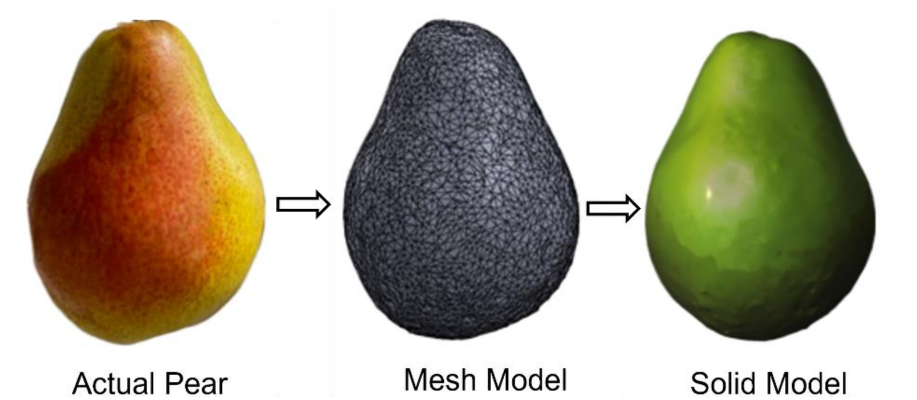


Fig. 1. Reverse engineering modeling procedure

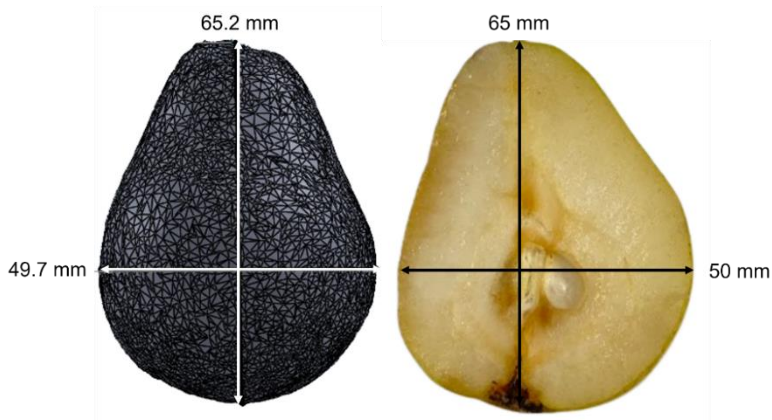


Fig. 2. Dimensions of pear 3D model and physical model

2.1.2 Determination of Fruit Mechanical Properties

Compression test was performed in order to determine the physical deformation behavior and mechanical properties of the pear. Cylindrical-shaped specimens were extracted from fresh pears purchased from the market. Specimens used in the test have dimensions of 20 mm diameter (d) and 20 mm height (h) as shown in compression test setup in Fig. 3. The specimen is compressed between two metallic plates, where the upper plate applies force to the specimen.

The test was performed using the universal materials testing machine (50 kN) LR50K Plus. The speed of the compression test was set to 3 mm/min as per ASAE S268.4 W/Corr. 1 DEC2000 which suggests a range of 2.5-30 mm/min as the nominal compression velocity for fruits and vegetables [10]. Based on this experiment, modulus of elasticity, strength and other mechanical properties were determined while physical parameters including mass and density were obtained by weighing and liquid exchange methods. Other parameters that were used for contact materials were obtained from ANSYS product material library as shown in Table 1 [22]. Bio-yield is the point which beyond the fruit permanent deformation will take place. Pears exhibit non-linear viscoelastic behavior under deformation. Viscoelasticity is time-dependent and complex phenomena where it would be difficult to simulate bruising (permanent formation) and nonlinearity at impact. Therefore, we have adopted in our study permanent plastic deformation as adopted in the literature [10]. An isotropic material model was used for the pear assuming a homogeneous structure of fruit flesh and skin [23].

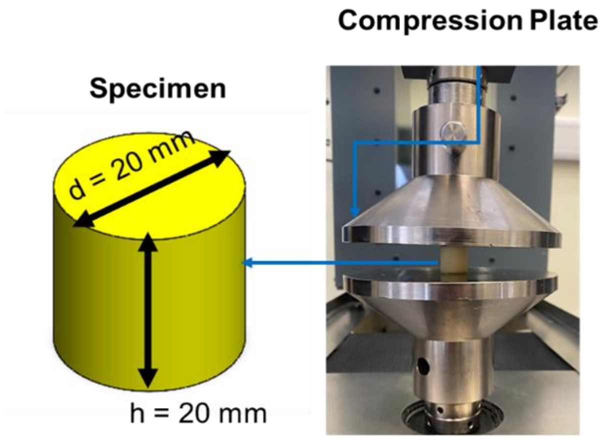


Fig. 3.Compression test setup

Table 1. Physical properties of materials

Material	Density (kg/m^3))	Modulus of elasticity (MPa)	Poisson ratio	Tensile Point (MPa)	Bio-yield Point (MPa)
Pear (Rosemary)	957^a	2.521 ^{b}	0.41 ^{c}	0.61 ^{d}	0.47 ^{d}
PLA	1240	3250	0.35	-	-

a Density data is obtained from experiment. b Young's modulus is defined as the ratio of stress to strain in the elastic region (Experimental). c Poisson's ratio [11]. d Compression Properties.

Fig. 4 shows the engineering stress-strain curve of compression test of rosemary fruit. Stress (σ) is defined as the applied force over the cross-sectional area, where strain (ε) is the ratio of material change of length to its original length. Equations of stress and strain are shown in equation (1). We can see that the compression experiment includes the linear elastic stage, plastic stage and failure stage. In the linear elastic stage, stress and strain are proportional. When applying the compressive load, the stress gradually increases linearly till the graph deviates from the straight-line behavior. This is where permanent deformation takes place and bio-yield starts which is shown in the yellow dashed line. The pear undergoes permanent deformation, and stress start to decrease as the material softens in the plastic deformation stage. The tensile point which is marked in red indicates the maximum stress that material can withstand before total failure. In the failure stages, tissue of pear fails due to excessive compression.

$$E = \frac{\sigma}{\varepsilon} = \frac{F/A}{\Delta L/L} = \frac{F\,L}{\Delta L\,A} \quad N.m^{-2} \tag{1}$$

Where E, F, A, ΔL, L, refer to modulus of elasticity, compressive force, cross-sectional area, displacement and initial length of specimen respectively.

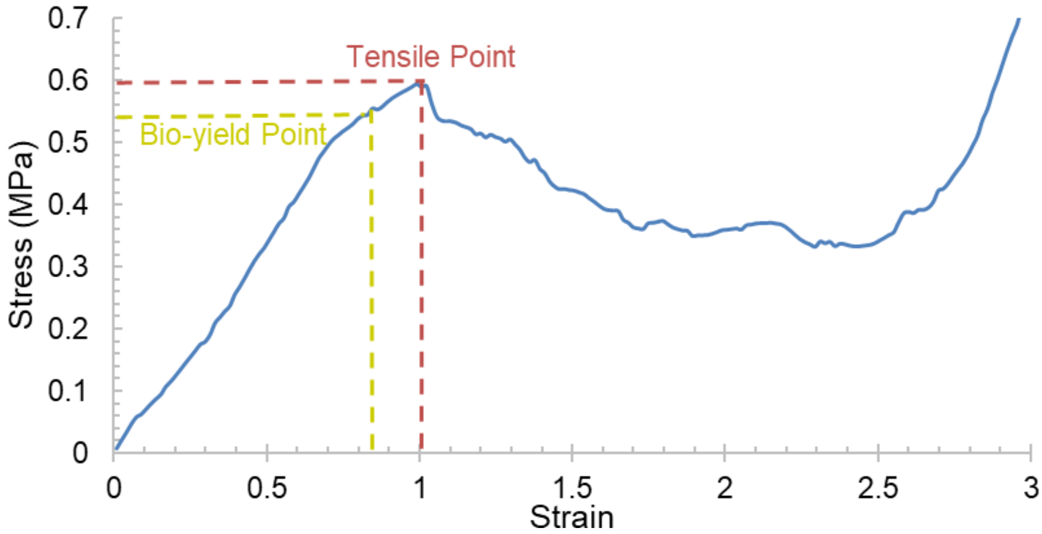


Fig. 4. Stress-strain curve of rosemary pear obtained from compression test

2.2 Finite Element Setup

In this study, a drop test method was utilized in order to evaluate bruises of the pear. Fruit drop simulations were performed in Explicit Dynamics ANSYS, Inc. Products 2021 R2 version software. Fig. 5 shows a schematic of the fruit drop simulation setup. The initial position of the fruit was set close to the rigid surface to reduce computational time and enhance calculations efficiency[3]. The contact type between the pear model and the rigid surface was determined as automatic, restricting the displacement of the rigid floor. A predetermined drop height of 0.5 meters was applied, in addition to the standard earth gravity effect. The initial velocity of the fruit can be calculated through the free fall formula $v = \sqrt{2gh}$ where g and h stand for gravity acceleration and fall height, respectively. Setting the solution, internal energy, equivalent von-mises stress and related deformation behavior were taken into account, and the simulation scene was set to 0.02 seconds in order to fully capture the dynamic response of pear during falling collision.

2.2.1 Mesh Sensitivity Analysis

Mesh is a critical phase in finite element modeling which involves dividing the geometric model into small volume units [24]. Increasing mesh element size increases the accuracy of the results, however, it leads to very long computational time.

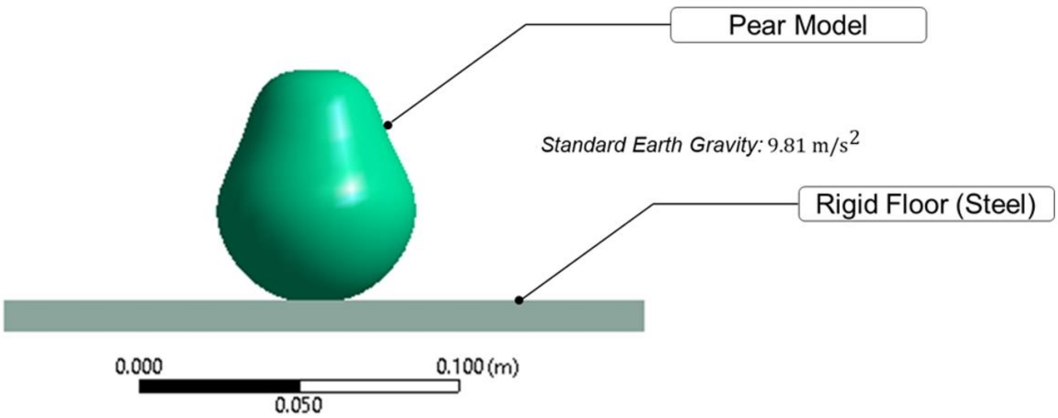


Fig. 5. Simulation setup

This is why a mesh sensitivity analysis was conducted in order to analyze the trade-off between mesh element size, results convergence, and computational time. Table 2 shows the influence of decreasing the element size on several factors. As we can see, the number of nodes and elements increase with the decrease of element size, meaning accuracy of model is improving. The stress values convergence as the mesh size increases. An element size of 1.5 mm is adopted for all simulation instances of this study.

Table 2. Influence of Element size on Elements, Nodes, and Equivalent Stress

Element Size (mm)	Elements	Nodes	Computation Time (mins)	Equivalent Von Mises Stress (MPa)
5	9874	6433	1	0.34
4	17848	12520	1.5	0.35
3	41127	27700	2	0.37
2.5	62494	39972	4	0.39
1.9	140347	94047	9	0.44
1.7	178211	117070	10	0.45
1.5	255003	170107	20	0.48
1.3	472981	323639	25	0.48

2.3 Bruising

The bench experimental bruise volume is calculated through obtaining the dimensions of bruise depth (h_b), and bruise diameter (d) (major and minor width: w_1 and w_2) after 48 hours after fruit drop [25]. Fig. 6 shows the measurements of bruise diameter and depth of the pear during bench experiment. The following formula was used to calculate bruise volume [26]:

$$BV = \frac{\pi}{6} d^2 h_b \tag{2}$$

Where d and h stand for bruise diameter and bruise depth respectively.

The bruise volume obtained from finite element simulation is determined through the extraction of all stress nodes where stress have exceeded the bio yield (0.4 MPa). The bruise percentage is identified as the ratio of bruised nodes to overall nodes. Bruise percentage is then multiplied by the pear volume to get bruise volume. Values of bruise volume are typically small values, as reported in the literature [20]. However, any minor variation in bruise volume calculations could significantly affect the fruit shelf-life and quality.

Fig. 6. Bench experiment bruise measurements: a) bruise diameter b) bruise depth

2.4 Proposed Packaging Design

The pear drop test presented in this study is validated with experimental setup in terms of bruise volume. Thus, this model can be used to propose a packaging design that can provides protection for pears from mechanical damage and external forces during transportation. The proposed packaging design is shown in Fig. 7. The design has a rigid triangular frame which encloses the fruit to prevent its direct contact with external surfaces or objects.

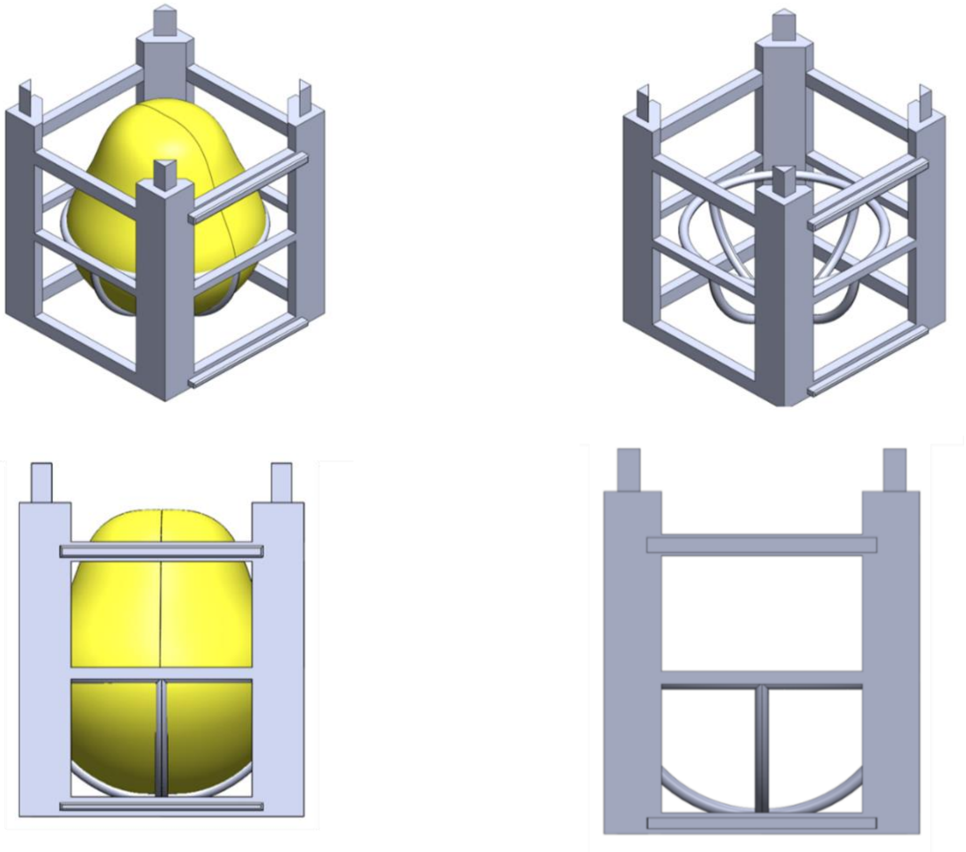


Fig. 7. Front and side view of proposed design

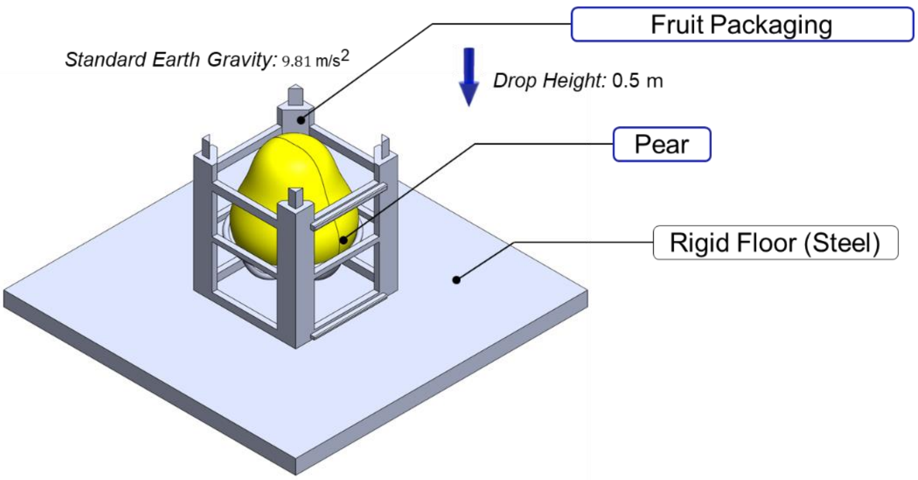


Fig. 8. Boundary conditions and simulation setup

The design includes rounded thin circular rings that can serve as shock-absorbing mechanisms. These rings would minimize stress on fruit. Furthermore, the design included holes, slots and pins to facilitate stacking, assembly and disassembly for modular units during transportation and handling operations. The assembly of the design with the pear and steel base was done in SolidWorks. The simulation setup of the FE model is similar to the setup presented in section 2.2. The effect of standard earth gravity was taken into consideration. The fruit along with the packaging structure were set to drop at 0.5 meters height on the rigid steel base. A schematic of the finite element model setup is illustrated in Fig. 8.

2.5 Response Surface Methodology

The proposed design proved its efficiency in reducing the bruises in pear. Therefore, a design of experiments is carried out in order to investigate the influence of design variables on bruise behavior. Response surface methodology is utilized to evaluate the bruising behavior subject to different design geometrical changes. Design of experiments is a robust statistical-based tool that helps analyze the effect of process parameters on specified properties[20,27].

Table 3. Factor levels for experimental design

Factor	Index	Level		
		-1	1	Unit
Structure Thickness (mm)	S_t	3	5	(mm)
Circular Thickness (mm)	C_t	3	7	(mm)

In this paper, central composite design (CCD) methodology is used that can build a second order polynomial without the need to use full factorial design. Two main factors are used in this experimental design: circular thickness (C_t), and structure thickness (S_t) as shown in Fig. 9. The factors along with their levels are presented in Table 3. The range of (C_t) and (S_t) were set to vary between 3mm to 7mm so the structure can remain lightweight. The influence of varying these factors is evaluated in order to optimize two responses: bruise volume (BV) and structure internal energy (IE). The pear bruising is directly related to the fruit shelf-life which we aim to extend. The internal energy of the structure measures the ability of structure to absorb impact so it is not transferred to the fruit in form of bruising. The statistical software Minitab is utilized to build the response surface methodology model. Nine different runs will be conducted for geometrical design combinations. The designs are modelled in the CAD modeling software SolidWorks. Finite element simulations will be conducted on ANSYS at pre-determined drop height of 0.5 meters.

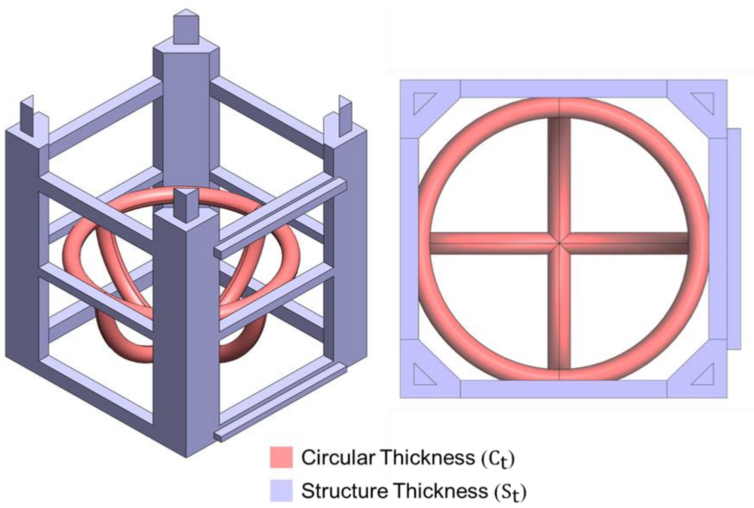


Fig. 9. Isometric view and top view of structure

3. Results

3.1 Experimental Validation (Drop Test)

The collision between the fruit and the contact steel plate after the fall was divided into the following stages: break-off contact, bounce and collision bruising as shown in Fig. 10. First, during the break-off contact, we can notice localized stress concentration at the pear-surface contact area. At the bounce phase, energy is distributed through the fruit where stress waves travel which will lead to internal damage. Finally, during the collision bruising, the fruit experiences residual stress, leading to a permeant tissue deformation, mainly due to the conversion of kinetic energy into plastic deformation. This process results in bruising where the material goes under irreversible deformation.

To further evaluate the accuracy of the fruit finite element model, bruise volume of bench experiment was compared to bruises obtained from simulations yielding in 19% error between FEA simulated bruise volume and experimental bruise volume with values of 1.45E-06 $m^3$and 1.18E-06 m^3 respectively. We have obtained a percentage error of 19% which is in line with range of values presented in the literature [25,28]. We can notice that the simulated bruise volume is slightly higher than the simulated bruise volume. This is because the bruise on the fruit cannot be immediately recognized by the naked eye after impact. The bruise is not recognized clearly until 24 hours at least have passed after the impact test [20,25]. Bruise volume in finite element simulations is obtained through extracting the nodes where which bio-yield limit is exceeded. Using ANSYS, the bruised regions were combined and extracted to CAD software in order to calculate mass, volume of bruised volume (Fig. 11).

3.2 FEA and RSM Results

Simulation instances were generated by varying both factors structure thickness and circular thickness in order to analyze their impact on bruise volume and structure internal energy. To assess the bruising in the fruit, it is crucial to investigate the absorbed internal energy by the package structure and optimize the impact absorption to achieve fruit protection. Table 4 lists the fruit and structure related energy, stress, and bruise details. We can notice that with the increase of structural thickness, the stress of the pear increases linearly. Increasing the structural thickness beyond 4 mm transfers more impact force to the fruit, leading to more bruising.

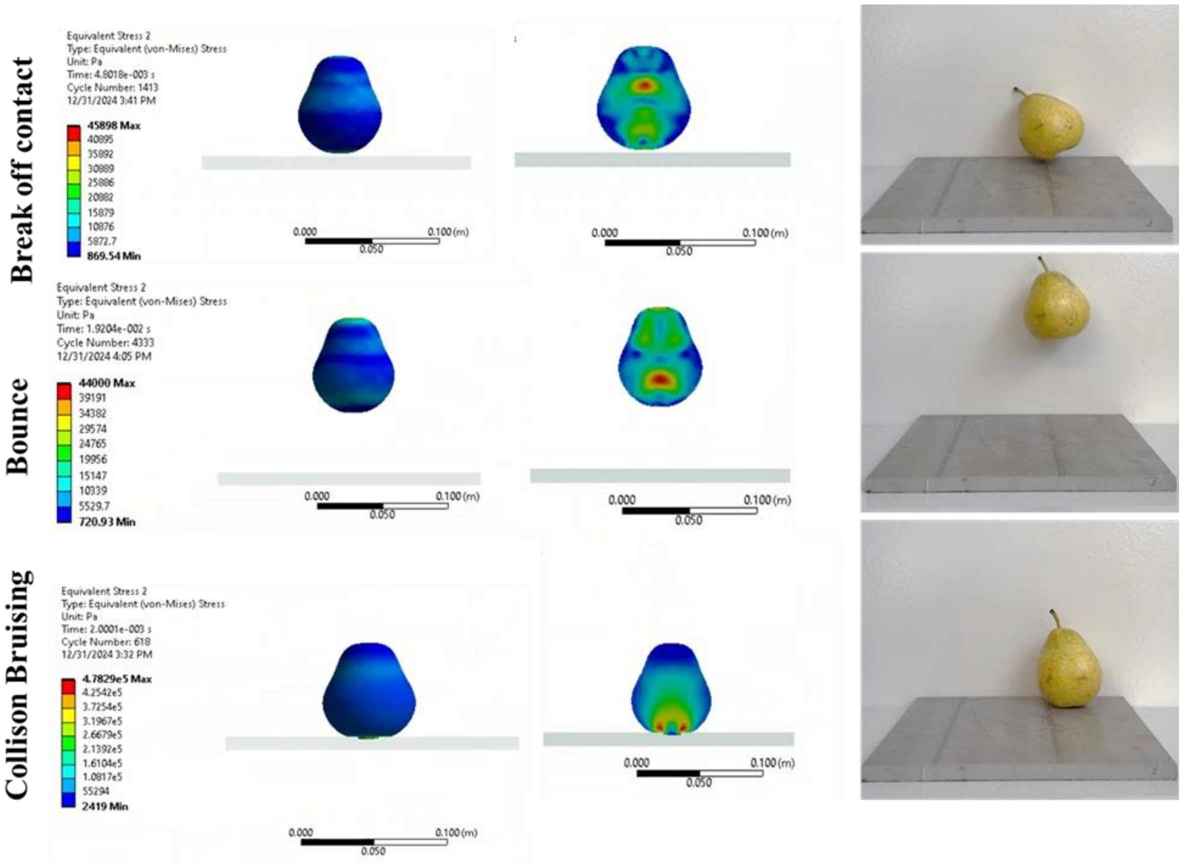


Fig. 10. Model validation: finite element drop test versus camera frames for fruit falling

Circular thickness (C_t) seems to have a negative impact on fruit bruising. Although increasing the thickness of circular rings will reduce localized stress and absorb impact energy, thicker rings transfer more energy to the fruit which leads to higher bruising. Thinner circular rings help balancing the rigidity of structure and energy absorption. The optimal design configuration which provides better cushioning for the pear is run instance #2 with structural thickness of 4mm and circular thickness of 3mm. This design minimizes the bruising in pears as it provides lowest bruised volume, mass and percentage. This structure has the ability to absorb impact energy with minimal force transmission to the fruit without being too rigid (internal energy = 0.34 J). The stress distribution of the structure is shown in Fig. 12. We can see that the stress is mainly concentrated at curved regions and connection point of circular rings, indicating that these areas are responsible for structural integrity. The stress at circular rings is considered moderate, which confirms their role to absorb impact forces.

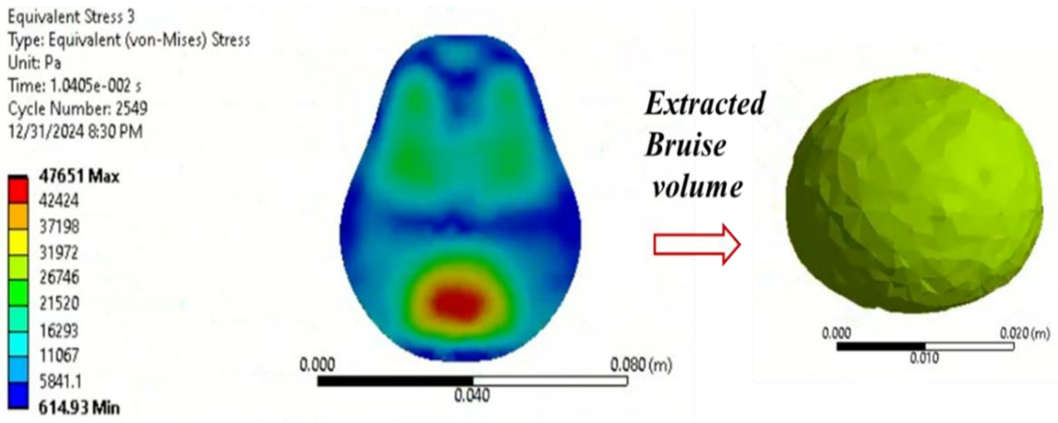


Fig. 11. Bruise volume extraction in simulations

Response surface methodology was performed where response surface, factorial, and contour plots were generated in order to visualize the relation of process parameters (C_t) and (S_t) on responses: bruise volume and structure internal energy as shown in Fig. 13, Fig. 14 and Fig. 15. The lowest bruise volume occurs when the structural thickness is around 4-5mm, and the circular thickness varies from 3mm to 5mm (Fig. 13 a). The structural internal energy increases with the increase of circular and structural thickness, because thicker structures tend to absorb more impact energy.

Table 4. Fruit and Structure Characteristics of Simulated Drop Impacts

Run	S_t (mm)	C_t (mm)	Fruit Stress (MPa)	Fruit IE (J)	Struct. Stress (MPa)	Struct. IE (J)	Bruising Percent. (%)	Bruised Volume (m^3)	Bruise d Mass (g)	BS ($m^3 \cdot J^{-1}$)
#1	3	3	0.47	0.38	53	0.38	0.010	1.37E-06	1.30	3.58E-06
#2	4	3	0.97	0.36	45.9	0.34	0.004	5.14E-07	0.48	1.34E-06
#3	5	3	1.03	0.65	37.28	0.42	0.004	5.84E-07	0.55	8.96E-07
#4	3	5	0.70	0.44	61.5	0.33	0.006	7.94E-07	0.75	1.80E-06
#5	4	5	0.65	0.44	61.8	0.37	0.005	7.44E-07	1.97	1.69E-06
#6	5	5	0.83	0.70	29.4	0.43	0.043	5.78E-06	5.49	8.27E-06
#7	3	7	0.66	0.60	52.3	0.32	0.022	2.93E-06	2.78	4.96E-06
#8	4	7	0.72	0.61	61.8	0.38	0.022	2.97E-06	2.82	4.87E-06
#9	5	7	1.00	0.88	32.87	0.44	0.017	2.33E-06	2.21	2.64E-06

Fig 14 shows the factorial plot for bruise volume and structure internal energy. Fig 14(a) shows a parabolic shape relation with structure thickness. When St increases from 3mm to 5mm, the bruise volume decreases, reaching minimum at St = 4mm, after which it starts to increase again. This means that a structure thickness of 4mm is the best one to reduce the volume of a bruise. Although thicker structures probably are able to distribute impact forces better, there is a limit up to which they still take in and give more energy to the fruit, thus larger bruises will appear. With reference to circular thickness (Ct), the bruise volume (Fig. 14, left) goes up as Ct ranges from 3.0 mm to 6.0 mm, which means that thicker circular rings induce more bruises. This can be explained by the fact that the thicker rings give more force to the pear at the time of the impact and thus more localized bruising occurs.

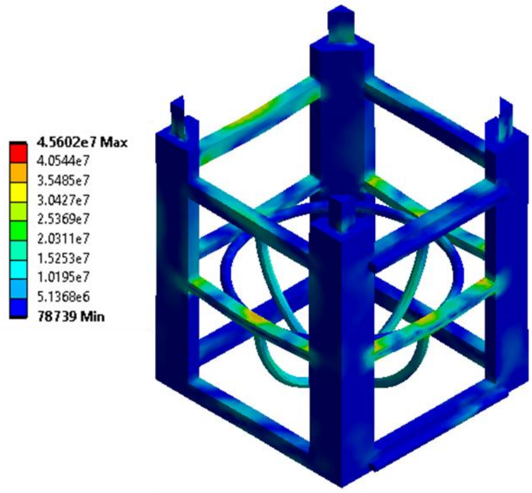
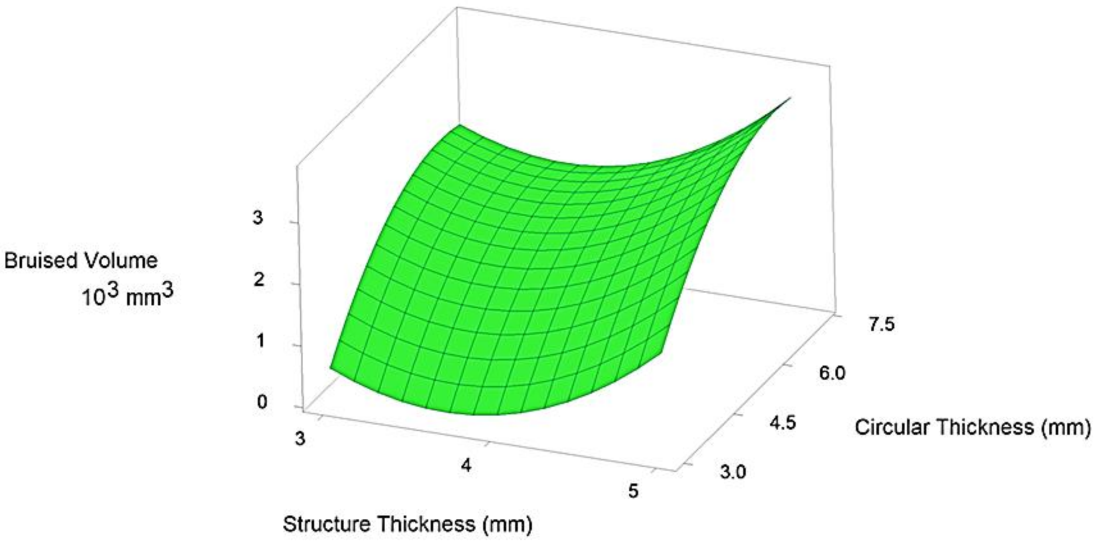
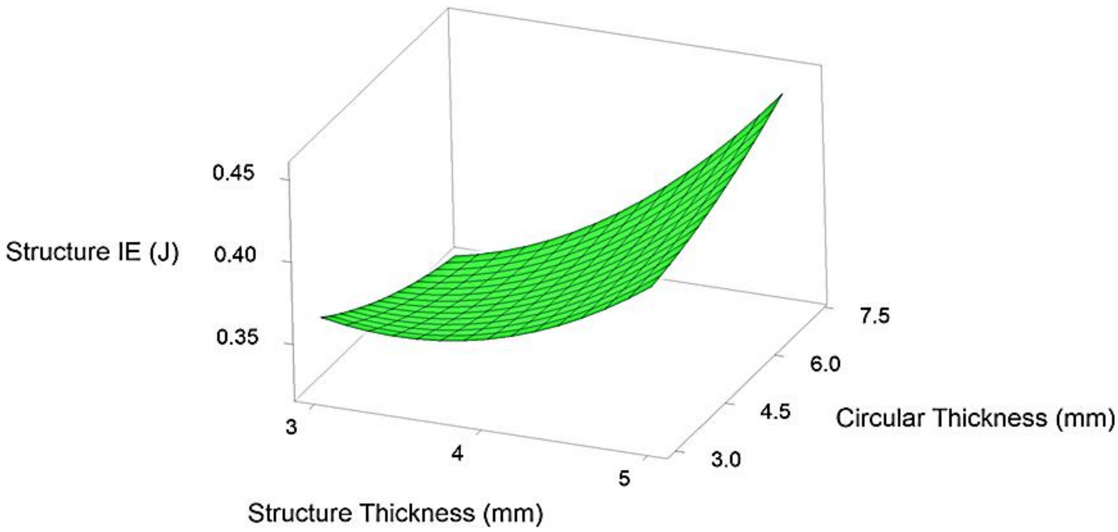


Fig. 12. Stress distribution of the optimal design



(a)



(b)

Fig. 13. Response surface plot for (a) bruise volume and (b) structure internal energy

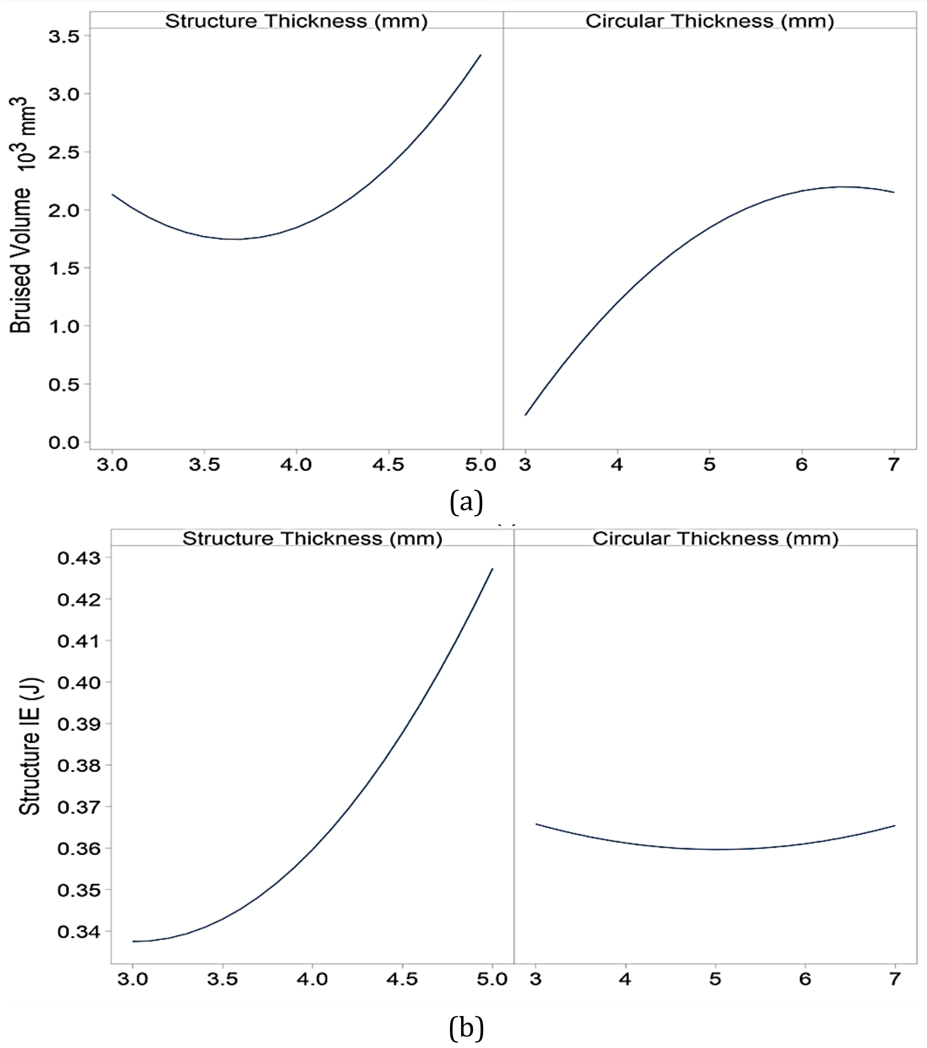


Fig. 14. Factorial plot for (a) bruise volume and (b) structure internal energy

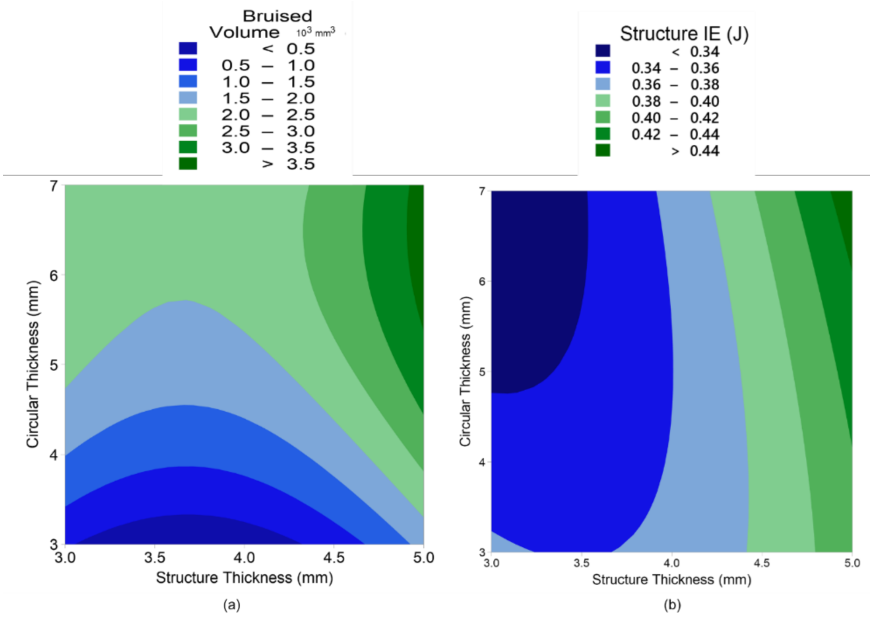


Fig. 15.Contour plot for (a) bruise volume and (b) structure internal energy

As for the internal energy (Fig. 14b), the energy of the structure is going up in line with St. As a result, the thicker the structures, the more the energy they get from the impact and the more they are able to store, naturally. Still, for Ct, the energy goes down a little until about Ct = 5.0 mm and then it starts going up again, which means that inserts with a thinner circular ring at first reduce the amount of the energy that they absorb, but when they become thicker it is still the case that they hold the most energy within the structure. Fig. 15 shows the contour plots, and indicates that minimal bruise volume and structural internal energy are achieved within the range of C_t (3 mm – 5 mm) and S_t (3 mm – 4 mm).

4. Discussion

Based on the obtained results from FEA and RSM, we can say that the variation of circular thickness (C_t) mainly affect the bruising volume, while structural thickness (S_t) affect the internal energy of the structure [25,28]. Circular thickness is responsible for the distribution of impact forces on the fruit. This is why, a circular thickness beyond 5 mm increases the bruise volume, and causes higher localized forces because of the excessive rigidity of the structure transferring impact to the fruit. Structural thickness controls how much energy is absorbed by the structure. Thicker structures tend to absorb more energy, providing better cushioning for fruits. However, 4 mm thickness and thick structures make the package too stiff and rigid which transfers force to the fruit. An internal energy greater than 0.42 joules leads to higher fruit bruising, suggesting excessive rigidity leads to poor energy dissipation which harms the fruit. That is why a trade-off between circular thickness and structural thickness is recommended in order to gain a balanced configuration which minimizes both fruit bruising and structure internal energy.

The optimal design configuration has a circular thickness of 3 mm and structural thickness of 4 mm. This design package achieves the lowest bruise volume leading to minimal damage of the pear. Less internal energy is exerted on the pear since the fruit internal energy is 0.36 Joules (considered one of the lowest energy values among run instances). The proposed package design is shown in Fig. 16. This design reduces bruising on the pear by about 65% compared to dropping the fruit on rigid floor, where bruise volume when the pear is dropped on the floor is 1.45E-06 m^3, whereas it is only 5.14E-07 m^3 when the fruit is dropped while attached to the proposed design. . Fig. 17 shows a sectional cut along the pear. We can observe that the bruises almost disappeared when attaching the fruit to the proposed design. This significant improvement in bruises minimization proves its efficiency enhancing the fruit quality and shelf-life.

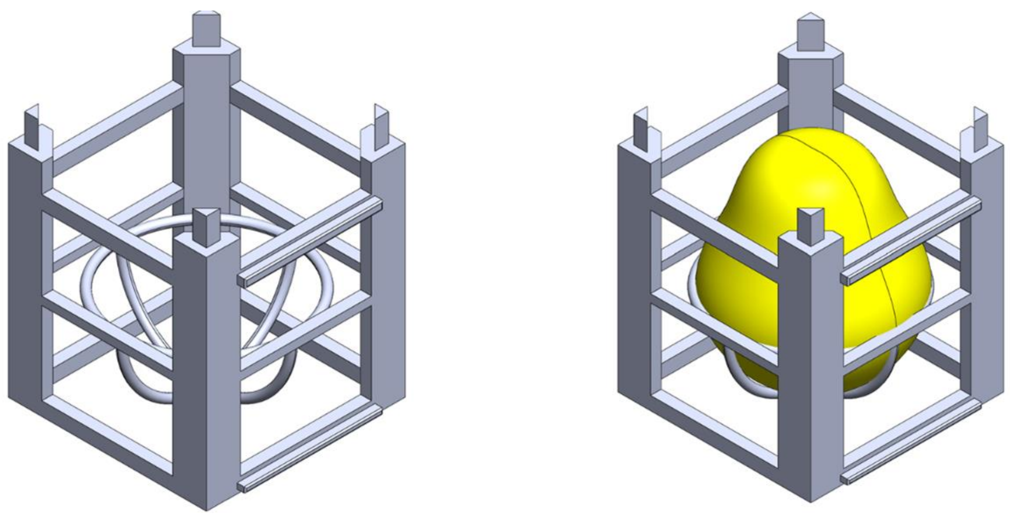
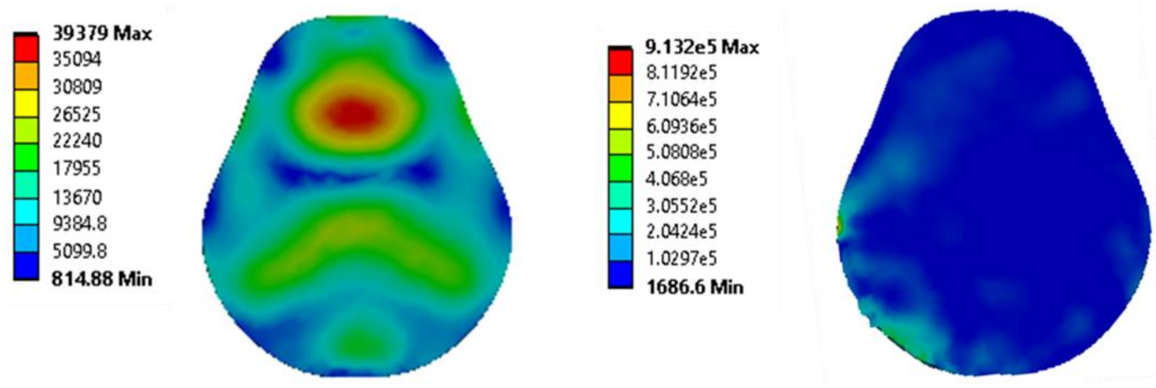


Fig. 16.Optimal proposed design for fruit packaging

The proposed design is made up of 3D printed PLA which facilitates the remanufacture, reuse, and recycling of this product. PLA is known to be biodegradable and requires minimal energy to be processed compared to other thermoplastics. Furthermore, the design has openings along each side which will allow for ventilation, which restricts humidity to spoil the fruit and therefore extend its shelf-life.

The proposed structure is designed to be adopted as a modular system (Fig. 18). Each cell unit is independent, and all units can be stacked and arranged together horizontally and vertically to form a whole fruit packaging box imitating traditional fruit packages. The package assembly and disassembly are facilitated with the availability of slots, holes and pins which are made at the top, bottom and side of the design.



(a) (b)

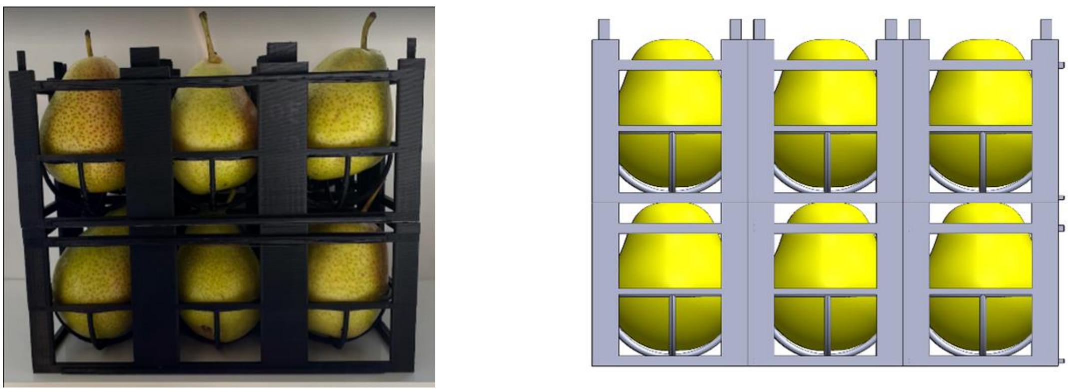
Fig. 17.Bruising distribution of (a) free pear and (b) pear attached to design

The modularity feature allows for flexibility, customization and adaptability depending on customer requirements, storage capacity and transportation constraints. The modular packaging design promotes efficient pears packaging as each unit cell has the ability to absorb shock individually preventing other fruit from damage due to compression forces during transportation.

4.1 Practical Implications

According to the results of the study, the proposed fruit packaging has proven its efficiency in pear protection and bruises minimization. However, the current practice in factories and organizations may not be fully ready to shift to the 3D printing technology adoption. The initial investment of 3D printing farm can be challenging in terms of installation cost, raw materials and skilled labor[29]. Furthermore, the plastic unit cost is considered higher compared to traditional cardboard or foam packaging. Although the production cost of the package may be a bit high, in the long-term run, the adoption of these packages would be beneficial since PLA is biodegradable [30], so packages can be reused multiple times.

Material-wise, the mechanical strength and resistance of PLA can degrade over time due to the exposure to heat and moisture. Thus, frequent packages replacement can be done once every period for the damaged units in order to maintain the structural integrity of packaging. From the supply chain perspective, packaging stations, production and assembly lines, warehousing systems may need some adjustments and reconfiguration. Labors and workforce will need training sessions to lean the proper handling and stacking of this kind of packages[31]. Through the proper planning and implementation for the recommended design packages, effective packaging methods can be achieved, promoting sustainability, flexibility and customization.



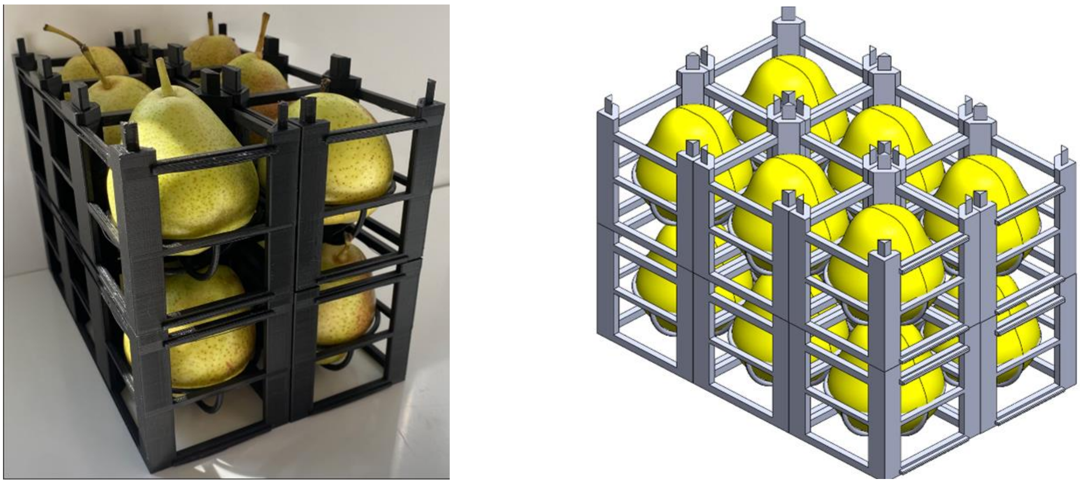


Fig. 18. Modular design FE and physical model

5. Conclusion

This paper had developed a pear finite element model through the use of reverse engineering modeling. Mechanical properties of the pear including young's modulus, density, and bio-yield limit were determined through compression mechanical testing. The fruit FE model was then validated with bench experimental setup with acceptable error value of 19%. Leveraging the validated FE model, a 3D printed PLA-based cushioning design structure was proposed that aims to minimize fruit bruising. Design of experiments was performed in order to optimize the fruit bruising and structure internal energy. The response surface methodology results had shown that around 3mm to 4mm thickness is recommended for circular and structure thickness of the design in order to maintain the structure rigidity to absorb the impact energy so fruit bruising and damage can be minimized.

The optimal proposed package had proved its efficiency in reducing fruit bruising by 65%. The design has openings along each side, allowing for ventilation. Furthermore, the single unit cell has slots and pins so multiple units can be assembled together to form a multi cellular package. The modularity feature allows for customization, and flexibility aligning with customers, retailers and distributors preferences and needs. The design is made from PLA promoting reusing, recyclability and sustainability.

Future work can focus on improving the accuracy of the pear finite element model in comparison to the physical model. In our study, the percent error is 19%, and future research could aim at reducing this value to develop more realistic models. PLA can exhibit low mechanical strength properties due to excessive loading or heat exposure. Therefore, the consideration of other polymers for fruit packaging can be investigated. Our study has tested the proposed design on rigid steel surface only, however for future work we can include other impact surfaces such as plastic, rubber, and wood. Investigating the effect of further process and geometric parameters that would affect the bruising in pears would provide deeper understanding and thus enhance packaging quality and effectiveness. Finally, potential future research can focus in the use of non-destructive methods such as machine learning and artificial intelligence tools to detect bruising in pears [32].

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