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Exploring Recycled Polyethylene Terephthalate (PET) Based Cushioning Design to Reduce Bruise Damage in Pears

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Abstract: Post-harvest activities, which include sorting, loading, unloading, and transporting, are potential factors that cause mechanical damage and bruises to fresh produce. This would directly impact fruit shelf-life and, therefore, cause economic losses. This study developed a finite element (FE) model for pear fruit where a steel impactor drop-based test was utilized. The FE model was validated by evaluating it as the experimental model in order to identify bruises of the pear fruit. Therefore, to minimize bruises on the pear fruit, a recycled polyethylene terephthalate (PET) spring-based design was proposed in order to serve as a cushioning design for pear fruits. Design of experiments and response surface methodology were performed in order to minimize the fruit bruise susceptibility response subject to different spring design parameters. The results revealed that reduced spring pitch and increased coil thickness would significantly minimize bruises of pear fruit. The recycled PET proposed design proved its efficiency in reducing FE pear fruit model bruises by about 50%. This study provides insights on assessing bruise susceptibility using finite element analysis and reusing plastic for fresh produce packaging, thus reducing loops in supply chains and achieving a circular economy.

Keywords: recycled polyethylene terephthalate; fruit cushion; packaging; bruising; mechanical damage; finite element analysis

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1. Introduction

Pear fruits are considered among the highly perishable agricultural products due to their sensitivity to inappropriate conditions during transportation, harvesting, and reloading [1]. Pear fruits have a soft texture compared with other fruits, which makes them highly likely to be mechanically damaged or bruised. Factors such as vibration, impact, puncture, and impact have the potential to cause mechanical damage to fruits throughout the post-harvest supply chain [2]. Bruising is the most common mechanical damage type, and it is a form of subcutaneous tissue failure that appears as discoloration in the affected areas and happens without rupturing the fruit's skin [3,4]. These bruises contribute to fruit quality deterioration and shelf-life reduction, which result in economic losses.

Various terms are used to quantify the level of fruit bruising. These terms include resistance, threshold, bruise susceptibility and bruise volume [5]. Bruise susceptibility (BS) is the most reported term in the literature [6]. BS is defined as the ratio of bruise volume to internally absorbed energy [7]. Numerous approaches, including the pendulum, spherical impactor, and drop impact tests, are being employed in order to characterize damage and estimate the bruise susceptibility of crops. Finite element analysis (FEA) is a powerful numerical technique that is used to predict how an object or product responds to forces, impacts, or vibrations [8]. Such numerical methods help simulate and investigate material behavior within given boundary conditions [3]. FEA-based drop impact tests have proven their efficiency and effectiveness in predicting bruise susceptibility, stress distribution, and deformation for a wide range of fruits and vegetables, including kiwi, fresh corn, blueberries and Goji, white radish, and pears [7,9–13].

Timely identification of bruises and mechanical damage of fresh produce is a key procedure that helps enhance harvest and post-harvest procedures, therefore extending shelf-life and maintaining fruit quality [2]. Putting forward effective and useful packaging methods would minimize fruit bruising and losses in the post-harvest supply chain. Packaging is an efficient approach that serves to protect fresh crops and lower losses throughout the supply chain. Research on packaging designs for fruit cushioning is evolving. A packaging design for the Hongmeiren orange fruit has been proposed [14], and an expandable polyethylene (EPE) board was used in order to create partitions between the fruits. Each fruit was wrapped tightly with PU polyurethane foam. Authors have stated that internal packaging provides better fruit protection compared with bulk fruit packaging.

Loss of citrus during transportation was reduced by about 60% when polypropylene-based crates were used for citrus packaging compared with polystyrene packages. Less environmental damage is associated with polystyrene crates, as they have the potential to be reusable and recyclable [15]. Foam-based packaging outperforms packages made from cardboard or rubber [16]. However, the performance of paper and foam board-based packaging alters depending on the fruit characteristics and tends to absorb moisture when not coated. Moreover, this type of packaging does not have the ability to be reused again and will end up being disposed of and landfilled, which will contribute to environmental damage. On the other hand, the adoption of polymer-based packages and reusable plastic containers leads to lower carbon emissions, less waste, and cost-effectiveness compared with corrugated fiberboard boxes [17,18]. Reusable plastic packages require 39% less energy, 95% less solid waste, and 29% less total greenhouse gas emissions compared with corrugated fiberboard boxes [2].

Studies in the literature have studied early bruise detection and pear fruit response due to impact loading using the pendulum impactor test [19], hyperspectral imaging [20], structured-illumination reflectance imaging [21], and CT scanning [22]. The drop test is a commonly used test that assesses and quantifies the damage and bruise susceptibility of fruits. Yousefi et al. [23] determined the bruised area of pear fruit with three different ripeness levels: unripe, ripe, and overripe. The authors experimented with the drop test at three different height levels, two orientations, and various impact surfaces. Salarikia et al. [3] analyzed the stress and strain performance of pear fruit exposed to drop scenarios. The authors also evaluated the impact of dropping the pear fruit on steel, wood, Perspex, and rubber at different drop orientations on contact force and stress and strain distributions. Celik [12] utilized the drop test method to evaluate the bruises of pear fruits of Ankara variety at different impact platforms, drop heights, and orientations. It was found that the minimum bruise susceptibility was dropping the fruit on a rubber-based platform with a 45-degree orientation at one-meter height. The impact damage index of Pucheng crisp pear fruits was investigated using drop impact tests of pear fruits throughout the harvest, transportation, and processing stages [16]. Factors including pressure area and average pressure were found to be associated with the severity of bruising. In this work, a drop impact FEA-based test was developed for the pear fruit-shaped FE model instead of the round-shaped pear fruit model to accurately predict pear fruit bruises [24]. The developed FE model will be evaluated with an experimental model, which was presented in our previous work [25].

Polyethylene terephthalate (PET) plastic is the most commonly used plastic around the globe, and it is used in containers and bottles for liquids and food. Inappropriate disposal of waste bottles takes hundreds of years to decompose in the environment and would harm wildlife and marine and human ecosystems. Significant efforts and initiatives are being settled in order to recycle and reuse plastic waste, such as the Reform company and the Belgian Yuma company, which produce sunglasses out of recycled polymers, and the US Army and marine research laboratories, which are repurposing plastic waste to 3D print it [26]. PET-based plastic waste bottles can be reused and converted into a 3D printing filament, which contributes to gaining environmental benefits and removing wastes from streams. This would close loops in supply chains and achieve a circular economy. Recycling PET represents a great candidate for promoting a circular economy. Waste bottles are collected, cleaned, and then melted and reformed into filaments, which can be used to produce a variety of products, including clothing, textiles, spare parts, and electronics. Through recycling PET, the focus of the circular economy is to keep materials in the loop, and products should be in use as long as possible.

The proposed study is set out to propose a packaging design for fruit made up from 3D printed recycled PET. The goal is to minimize fruit bruises and improve shelf-life by making use of plastic waste to print cushioning design for pear fruits. The FE model used to model the fruit drop test and quantify the bruise susceptibility was validated with the experimental setup presented in our previous work [25].

The literature lacks cushioning systems and packaging designs for certain fruits that have soft textures, such as pears or fruits that are irregular in shape. Research has proven that package type would greatly impact the cushioning performance of pear fruits [27]. Furthermore, PET-based packages have proven their performance in reducing post-harvest damage and minimizing bruises on Andean blackberries [28]. Customized designs of biodegradable or reusable packages would minimize fruit losses and damage in the post-harvest supply chain [2].

Indeed, more research is needed to explore biodegradable, well-cushioned materials to replace existing ones [14]. The use of plastic packaging is increasing thanks to its reusability and recyclability. Therefore, optimization and customization of packaging designs would mitigate fruit damage and loss. The implementation of solutions that support close loops in supply chains and achieve a circular economy would provide benefits for all supply chain entities [15]. This study contributes in the following ways:

- Developing pear fruit drop impact test finite element model;
- Evaluating the FE model with an experimental model in terms of bruise volume and bruise susceptibility prediction;
- Proposing a spiral-based packaging design for pear fruits produced from recycled PET plastic waste;
- Investigating the influence of process spiral design parameters on pear fruit bruise susceptibility and understanding fruit spring behavior through the design of experiments and response surface methodology;
- Providing insights on cushioning and modular plastic packaging aspects based on the proposed design.

Figure 1 illustrates the general flow of how thus study was conducted in a step-by-step manner. The rest of the paper is organized as follows. Section 2 presents the methodology employed to conduct this study. Section 3 includes the key results and study insights in discussion. Conclusions and potential future work are provided in Section 4.

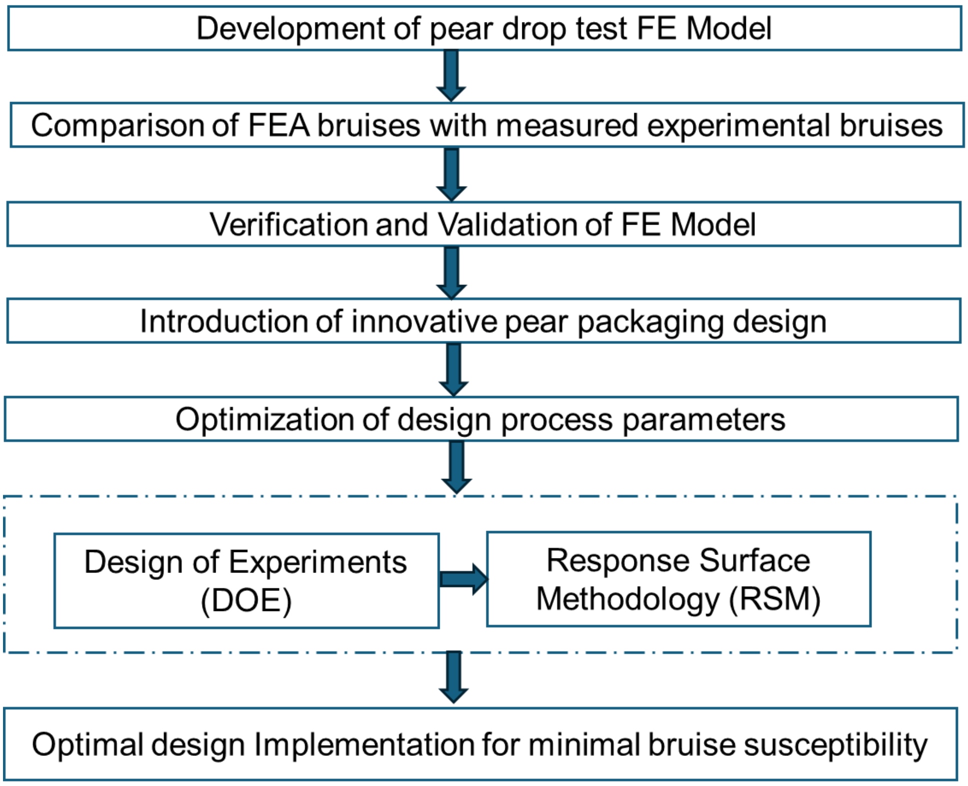

Figure 1. Flowchart of the proposed study.

2. Materials and Methods

2.1. Finite Element Modeling (FEM)

In this study, a drop impact test was employed in order to identify bruise-related calculations associated with pear fruit. Extending our previous work [25], the bruise susceptibility of pear fruit was studied experimentally by freely dropping a steel impactor into the pear fruit at three different height levels: 20 cm, 40 cm, and 60 cm. The schematic experimental setup is shown in Figure 2. The *Pyrus communis* pear variety "D'Anjou" was selected for this study. A total of 129 pear samples were selected according to their uniform color, shape, and surface condition. Each pear sample weighed an average of 163.12 $\pm$ 4.26 g. In our previous work, we investigated the influence of pear fruit drop impact on bruise volume, bruise susceptibility, color, and firmness during a 14-day storage period. Color measurements were taken six times per sample, with an average of 104 readings per day. On the other hand, the firmness was checked every 2 days at intervals throughout the experiment. In this work, we replicated the experiment with the use of a finite element analysis tool in order to verify the results and validate the finite element (FE) model.

The pear fruit was modeled using the SolidWorks 2023 SP 2.1 3D computer-aided design software. The 3D model of the pear fruit, along with its dimensions and properties, are shown in Figure 3a. The drop impact test of a steel ball impactor of 110 g mass was modeled in ANSYS 2022 R2 Workbench version 22.2.0. Fresh produce and agricultural products exhibit non-linear viscoelastic behavior. In this study, the elastic–plastic material model was adopted for the pear, where permanent plastic deformation can be simulated [12]. The material properties associated with each material used in this study are listed in Table 1 The FE model, along with the boundary conditions, are presented in Figure 3b. The steel ball was set to drop at a predetermined height, taking into consideration the standard earth gravity effect. Furthermore, the pear fruit was fixed from the bottom surface on the contact area with the floor.

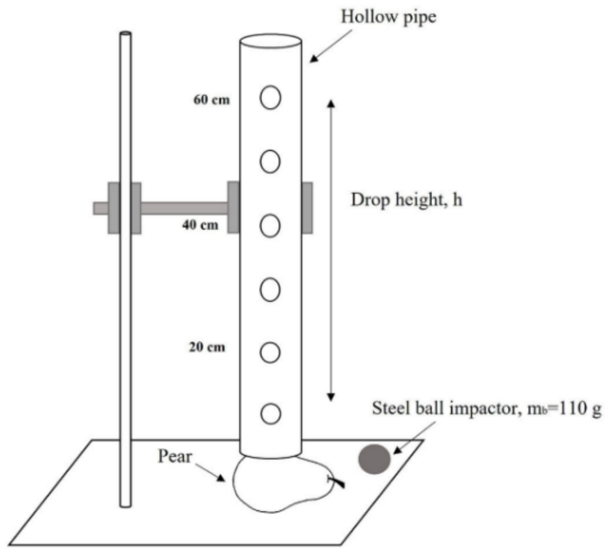

Figure 2. Physical experimental setup by Pathare et al. [25].

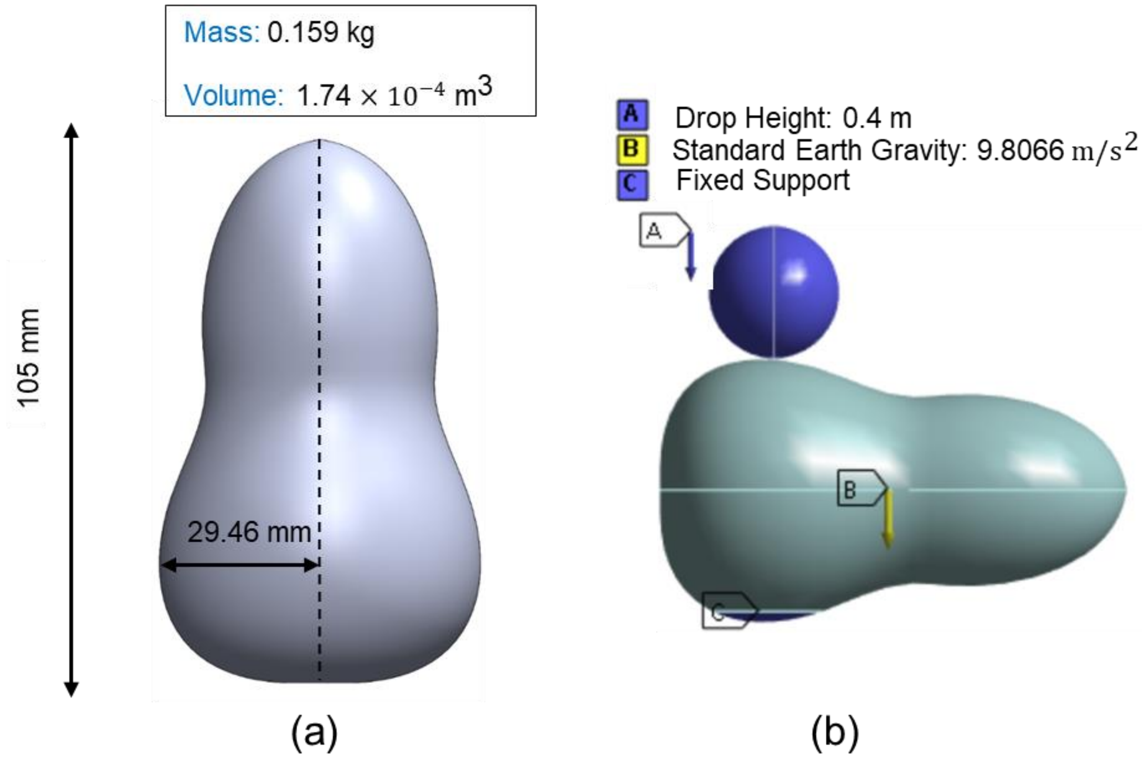

Figure 3. (**a**) 3D model and dimensions of the pear fruit. (**b**) FE model and boundary conditions.

Table 1. Material properties used in this study.

Material	Modulus of Elasticity (MPa)	Density ($\frac{kg}{m^3}$)	Poisson's Ratio
Pear fruit [23]	8.74	910	0.4
Structural steel [29]	2×10^{11}	7850	0.3
PET [30]	3200	1190	0.35
Poplar Wood [12]	8400	4000	0.318

After conducting the drop test experiment, bruise areas were marked on the pear fruit, and each pear fruit was sliced from the middle in order to perform bruise measurements.

To obtain the bruise volume through FEA, the stress nodes that exceed the bio yield stress (0.3 MPa for pear fruit [12]) indicate the occurrence of bruising at maximum stress during collision. The sum of bruises in these nodes was used to obtain bruise volume and bruise susceptibility. The percentage of bruising is the ratio of bruised nodes to overall nodes. We can obtain the bruised mass by multiplying the bruising percentage by the known mass of the fruit. Bruise susceptibility (BS) is obtained through the following equation: BV is the bruise volume, and E is the internal energy of the pear fruit. BS values are typically very small values, as reported in the literature (9.56×10^{-6}, 1.59×10^{-5}, 1.62×10^{-5}) [12]. However, any small change in BS values has a significant impact on fruit shelf-life.

$$\mathrm{BS} = \frac{\mathrm{BV}}{E}\ (\mathrm{m}^3 \cdot \mathrm{J}^{-1}) \tag{1}$$

In order to calculate the resulted energy from drop impact (E), the following equation was used as follows:

$$E = m \times g \times \mathrm{h}\ (\mathrm{J}) \tag{2}$$

where m represents the mass of the steel ball impactor in kilograms, g is the gravitational force ($g = 9.81\ \mathrm{m/s^2}$), and h is the predetermined drop height in meters.

2.2. Innovative Packaging Design

The pear fruit FE model presented in this paper was validated with the experimental model; therefore, we can make use of this model in order to design a cushioning system for pear fruit protection from mechanical damage.

Various methods are used to protect the fruit from mechanical damage, such as plastic or foam containers, cartons, or wooden boxes as external packaging methods. There are also internal packaging ways, like shredding paper, liner, plastic tray, or air column bags [2]. This study proposes a spiral-based packaging design for pear fruit, which serves as an internal packaging and could be further optimized as an external package. This design was made from recycled PET plastic bottles, which helps achieve sustainability and a circular economy. Furthermore, this design has the potential to allow ventilation for the fruit and, therefore, extend its shelf-life.

An initial spiral design was modeled in SolidWorks and evaluated with a pear fruit falling freely on a wooden base, as shown in Figure 4. The drop height was selected as 0.5 m and was fixed throughout the rest of the simulation instances to fix the simulation setup and to allow for fair performance comparison. Table 2 illustrates the bruise susceptibility for each pear fruit with the design and without it. We can observe that there was a 5% decrease in the bruise susceptibility of the pear fruit. Therefore, the proposed design has the potential to protect pear fruits from bruising. Further analysis and parameter optimization can be conducted on the suggested design.

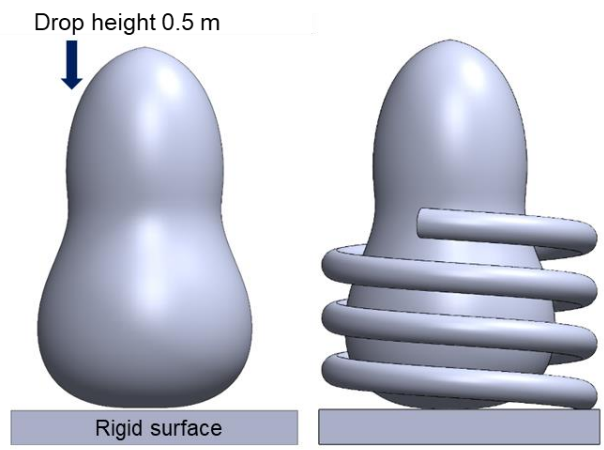

Figure 4. Free pear fruit versus pear fruit attached to the proposed design.

Table 2. Comparison of the bruise susceptibility of pear with the proposed design and without it.

	Pear Fruit Only	Pear Fruit Attached with Proposed Design	Percent Decrease
Bruise Susceptibility ($m^3 \cdot J^{-1}$)	1.94×10^{-5}	2.04×10^{-5}	5%

2.2.1. Mesh Sensitivity Analysis

The selection of the appropriate mesh element size in FEA would increase the accuracy of the results. However, smaller element sizes would increase simulation computational time. Therefore, mesh sensitivity analysis was conducted in order to find the optimal trade-off between computational time and results accuracy. Figure 5 shows the relationship between pear fruit impact energy and computational time across different element sizes. We can observe that computational time starts to increase exponentially after a 2.5 mm mesh size. At a 1.5 mm size, internal energy values and equivalent stress values start to remain steady and converge. The increase in nodes and number of elements with the reduction in element size is shown in Table 3. An element size of 1.5 mm will be adopted for all simulation instances performed in this study.

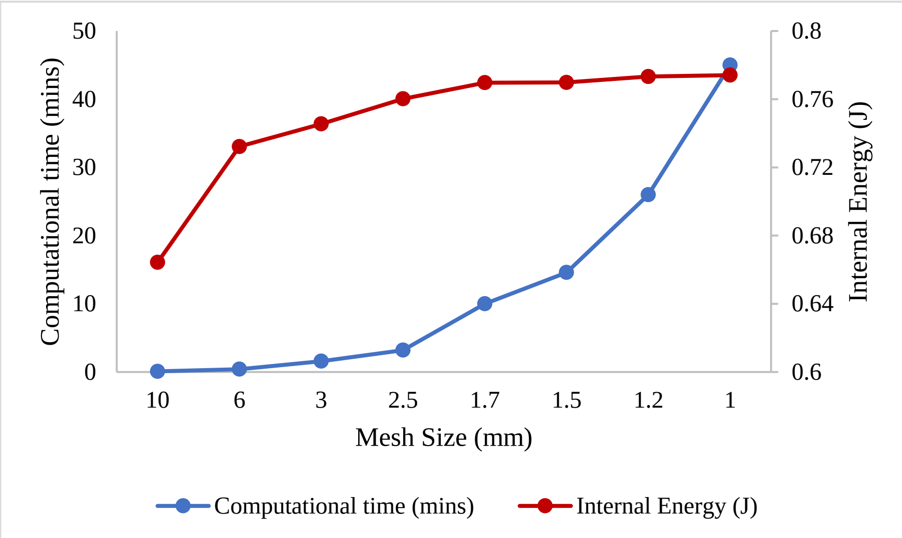

Figure 5. Fruit impact energy vs. simulation computational time.

Table 3. Effect of element size on equivalent stress, number of elements, and nodes.

Element Size (mm)	Equivalent Von Mises Stress (MPa)	Elements	Nodes
10	0.53	1521	512
6	0.67	5867	1836
3	0.73	35,543	10,268
2.5	0.74	53,572	14,958
1.7	0.76	141,145	40,622
1.5	0.76	197,471	57,106
1.2	0.77	337,832	101,138
1	0.77	515,890	155,264

2.2.2. Response Surface Methodology

The proposed design in the previous section proved its improved performance in terms of bruise-related calculations. However, spiral designs with different design parameters may yield different result performances. Therefore, a design of experiments for spiral design parameters was carried out in order to optimize the bruise susceptibility of the pear fruit. Figure 6 illustrates the terms and parameters of a typical spring. The outside diameter was fixed at 60 mm for all designs based on the pear fruit FE model dimensions. A value of 60 mm was selected to ensure the optimal fit of the pear fruit. Wire diameter, pitch, and revolution were the factors that were tested and optimized in the design of experiments in order to minimize the response, which is the bruise susceptibility of the pear fruit.

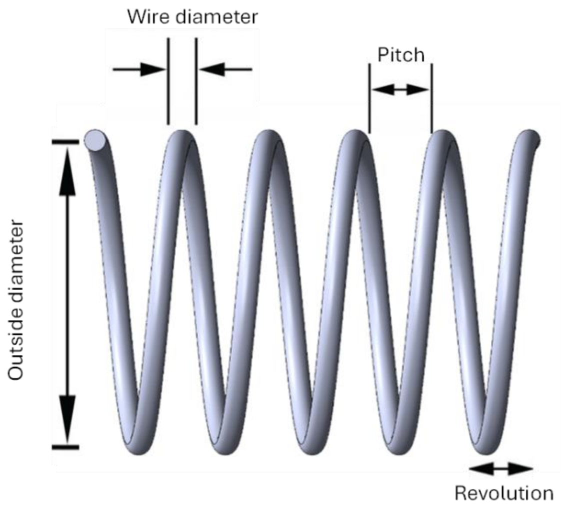

Figure 6. Schematic representation of spring parameters terminology.

In this research, response surface methodology was utilized in order to assess the behavior of spiral based on pear fruit bruise susceptibility. The influence of spring design parameters on fruit bruises will be evaluated, to gain insights into how recycled PET-based structures would affect fruit bruising.

The design of experiments is a powerful statistical tool that helps analyze the influence of process parameters on specified properties [31]. Central composite design (CCD), also known as the Box–Wilson central composite design, is a commonly used methodology to build a second-order polynomial for response variables without the use of the complete full factorial design [32].

In this study, CCD was utilized as the experimental design, taking into consideration the parameters wire diameter (D), pitch (P), and number of revolutions (R) in order to optimize the bruise susceptibility (BS) response. The correlation between D, R, and P and BS was evaluated using response surface methodology (RSM) on the statistical platform Minitab. Levels and units for each factor are presented in Table 4. According to CCD, a total of 20 experiments were generated, where the spiral structure for each run was designed in SolidWorks and imported into ANSYS workbench for drop impact test simulation in order to determine the bruise susceptibility of the pear fruit associated with each spiral design. Figure A1 (attached in Appendix A) illustrates the 3D design model for each design generated using CCD. The pear fruit and spring were set to drop at a predetermined height of 0.5 m for all experiments. The boundary condition of the problem was setting the wooden base as a fixed support, where the effect of the Earth's gravity was taken into consideration.

Table 4. Factors levels for experimental design.

Factor	Index	Level		Unit
		−1	1	
Wire diameter	D	5	12	(mm)
Pitch	P	10	20	(mm)
Number of revolutions	R	5	10	-

3. Results

3.1. FEM

Drop process, internal energy, and bruise volume were analyzed. Bruise volume and bruise susceptibility were obtained from the elements whose stress exceeded the bio yield stress. The impact energy of steel balls resulting from drop impact theoretically and through FEM are presented in Table 5. The error between theoretical and simulation values was less than 5%, indicating that FEA simulations can be reliable and trustworthy. Figure 7 shows a cross-sectional view of the pear fruit at the highest stress contact moment. Results indicate that bruising occurs mostly at the upper half of the pear fruit, specifically in the contact area where bio yield stress is exceeded. Unlike FEA, the bruising of pear tissue injury cannot be seen immediately by the naked eye through simple visual inspection. Bruising damage can be detected and measured after some hours, which may lead to incorrect or inaccurate detection [5]. Finally, Table 6 compares bruise volume (BV) and bruise susceptibility (BS) based on experimental measurements and FEA-based simulations. The absolute percentage error between observed and simulated values varied between 9% and 22%. We can observe that simulated bruise volume values were slightly higher than the measured ones. This can be explained as some bruises on the pear fruit cannot be recognized by the naked eye, as the bruise on the fruit is not clearly recognizable on the first storage day of the fruit, which results in a negative deviation of bruise calculations through experimental measurements [7]. Similarly, we can see that measured bruise susceptibility values underreported the FEA values, where minimum and maximum values of error were 13% and 25%, respectively. This is due to the neglect of contact energy since it has a low value. Simulated absorbed energy would be higher than the measured values, and therefore, measured BS values are lower than simulated ones, and percent errors were enlarged compared with bruise volume errors. Overall, the percent error between measured and simulated bruise calculations is considered acceptable, which supports the validation of the proposed FE model and its ability to predict the bruise susceptibility of pear fruits.

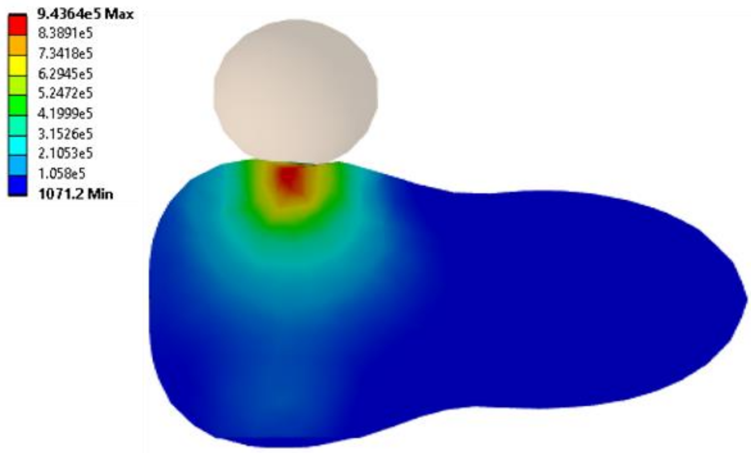

Figure 7. Simulation visualization output at max stress point (time = 1.5×10^{-3} s) at 40 cm drop height.

Table 5. Impact energy at different drop heights.

Drop Height (cm)	Theoretical Energy (J)	Simulated Energy (J)	Error (%)
20	0.215	0.213	1%
40	0.431	0.413	4%
60	0.647	0.620	4%

Table 6. Bruise volume of pear fruit at three different drop heights.

	Bruise Volume (m^3)			Bruise Susceptibility ($m^3 \cdot J^{-1}$)		
Drop Height (cm)	Measured BV	Simulated BV	Error (%)	Measured BS	Simulated BS	Error (%)
20	3.20×10^{-5}	3.77×10^{-5}	15%	1.49×10^{-4}	1.77×10^{-4}	16%
40	5.72×10^{-5}	7.38×10^{-5}	22%	1.33×10^{-4}	1.78×10^{-4}	26%
60	6.30×10^{-5}	6.93×10^{-5}	9%	9.74×10^{-5}	1.12×10^{-4}	13%

3.2. Response Surface Methodology (RSM)

Table 7 lists the design of experiments (DOE) factors, along with the bruise susceptibility obtained from FEA simulation. The main effect of independent parameters on bruise susceptibility is shown in Figure 8. Based on Figure 8, we can see that pitch (P) and wire diameter (D) are the two most influential parameters of pear fruit bruise susceptibility. However, the number of coil revolutions does not have a great significance on bruise susceptibility. To visualize the effect of process parameters comprehensively, response surface graphs were developed and presented in Figure 9. Figure 9 shows that increasing wire diameter (D) and decreasing pitch result in minimal bruise susceptibility. We can notice that bruise susceptibility is not highly sensitive to the change in the number of revolutions (R). Minimum BS can be achieved using a higher wire diameter and the lowest pitch distance.

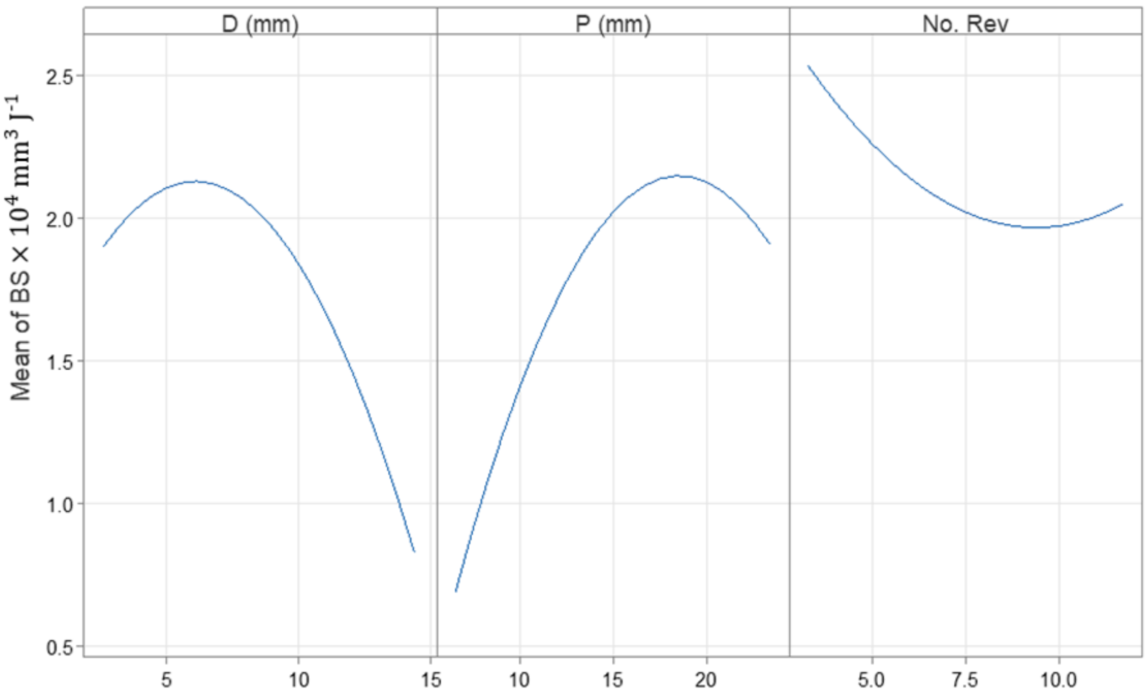

Figure 8. Main effect plot for process parameters.

Table 7. FEA and RSM predicted response and factors of experimental design.

Run	Independent Variables			Response
	D (mm)	P (mm)	No. of Rev	Bruise Susceptibility (10^4 mm^3 J^{-1})
1	12.0	20.0	10.0	1.96
2	8.5	15.0	7.5	2.03
3	5.0	10.0	5.0	1.99
4	2.6	15.0	7.5	2.00
5	14.4	15.0	7.5	0.22
6	8.5	15.0	7.5	2.03
7	8.5	15.0	7.5	2.03
8	8.5	15.0	11.7	2.04
9	8.5	6.6	7.5	0.03
10	8.5	15.0	7.5	2.03
11	8.5	15.0	7.5	2.03
12	8.5	15.0	7.5	2.03
13	8.5	15.0	3.3	2.04
14	5.0	10.0	10.0	1.97
15	8.5	23.4	7.5	2.06
16	12.0	10.0	5.0	2.15
17	12.0	10.0	10.0	0.37
18	5.0	20.0	10.0	1.96
19	12.0	20.0	5.0	2.09
20	5.0	20.0	5.0	1.98

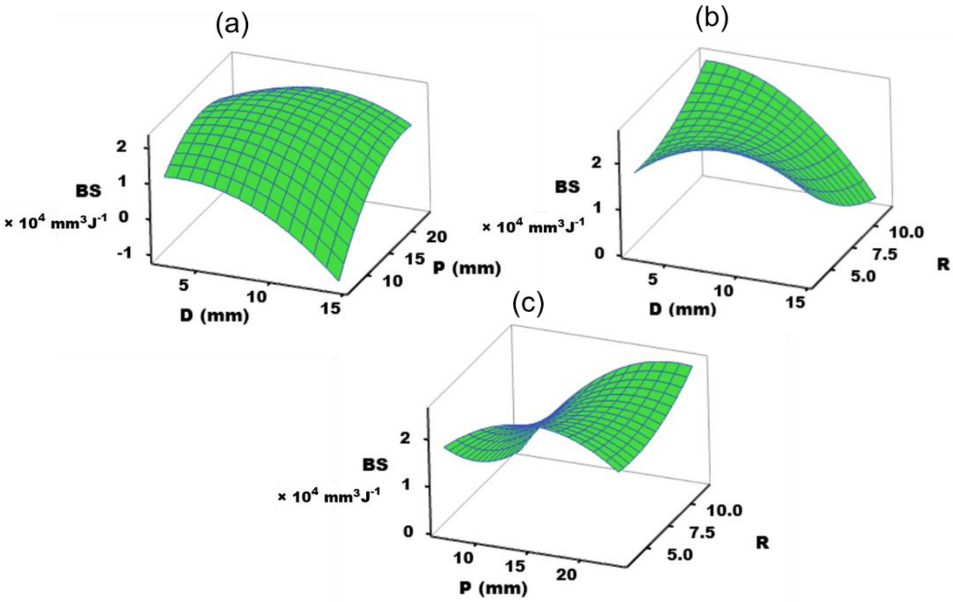

Figure 9. Response surface plots for bruise susceptibility of (**a**) diameter and pitch, (**b**) diameter and number of revolutions, and (**c**) pitch and number of revolutions.

3.3. Optimal Design

Based on RSM, we gained insights into how wire diameter, pitch, and number of revolutions can influence the bruise susceptibility of the pear fruit. The proposed packaging structure was designed in SolidWorks based on the way spring parameters affect the pear fruit bruises behavior. Lower pitch distance and thicker wire diameter would result in minimal bruise susceptibility. The wire diameter of the proposed design was set as 3 mm so that the spring could be flexible and compressed when load was applied. The geometry of the proposed design is shown in Figure 10. The design is spiral and attached to a rectangular base with dimensions of 64 × 64 × 4 mm. The spring has a variable pitch, a variable diameter, and 13 revolutions in total. Spring design parameters are listed in Table 8.

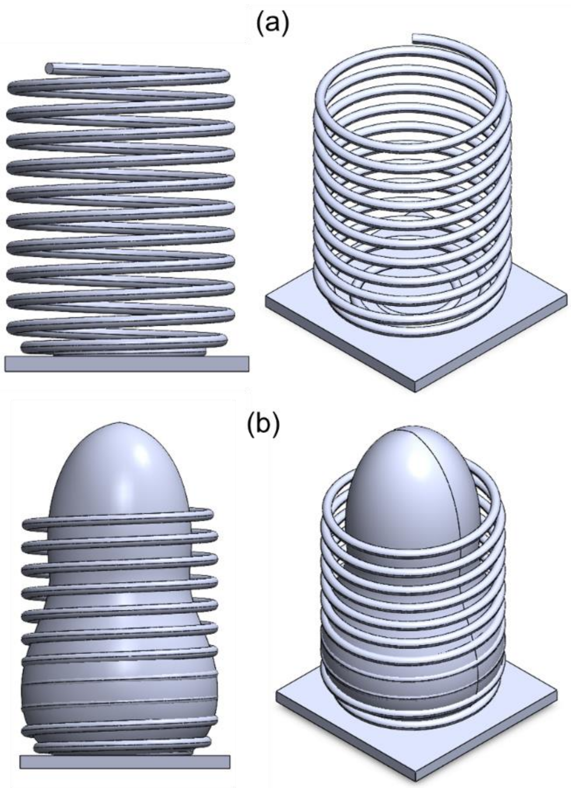

Figure 10. Front and isometric views of proposed packaging design (**a**) without pear fruit and (**b**) with pear fruit.

A drop impact test was performed on the pear fruit attached to the new design in order to assess the design performance in terms of bruises. The pear fruit, along with the design, were set to drop at a predetermined height of 0.5 and 1 m. The structure was set to drop on a wooden-based platform, which represented the fixed support boundary condition. Finally, the standard earth gravity effect was taken into consideration in the simulation setup. A schematic representation of the FE model, along with boundary conditions, is shown in Figure 11.

Table 9 shows the bruise volume, mass, and bruise susceptibility of free pear fruit versus pear fruit attached to the proposed design for half and one-meter drop heights. The fruit attached to the design outperformed the free pear fruit by almost half (50%) in terms of bruises.

Figure 12 shows the pear fruit bruise location after performing a sectional cut along the y-axis. The bruises in the free pear fruit are obvious with the green, yellow, orange, and red regions where stress has exceeded the bio yield point (0.3 MPa). However, we can observe that bruises significantly reduced when pear fruit was attached to the spring design. Bruises were very minimal, as there were no orange or red regions of bio yield stress.

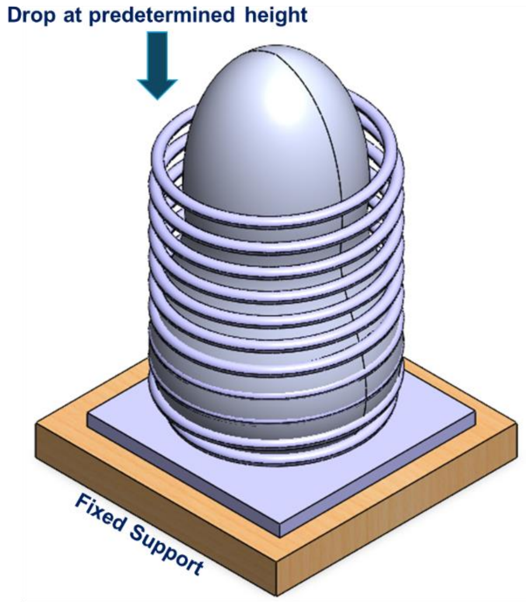

Figure 11. Boundary conditions of pear attached to design FE model.

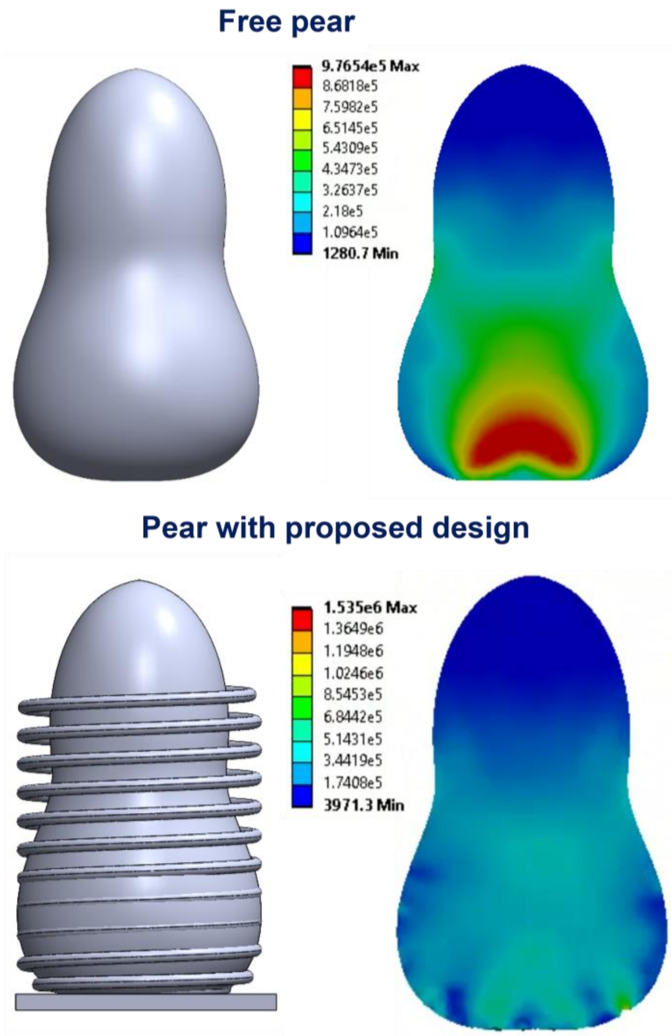

Figure 12. Stress and bruises distribution of free versus pear with design.

Table 8. Proposed design parameters.

Pitch (mm)	Number of Revolutions	Diameter (mm)
7 mm	1	57 mm
7 mm	10	57 mm
2 mm	11	49 mm
2 mm	12	30 mm
2 mm	13	20 mm

Table 9. Bruise volume, mass, and susceptibility using the proposed design versus free pear fruit.

	Drop Height					
	0.5 m			1 m		
	Pear Fruit Only	Pear Fruit with Design	Percent Improvement	Pear Fruit Only	Pear Fruit with Design	Percent Improvement
Bruise Volume (m^3)	1.49×10^{-5}	7.42×10^{-6}	50%	5.24×10^{-5}	4.14052×10^{-5}	21%
Bruise Mass (kg)	1.99×10^{-2}	9.93×10^{-3}	50%	6.98×10^{-2}	5.52×10^{-2}	21%
Bruise Susceptibility ($m^3 \cdot J^{-1}$)	1.94×10^{-5}	1.10×10^{-5}	43%	3.45×10^{-5}	3.01743×10^{-5}	13%

4. Discussion

In this paper, a pear-shaped fruit FE model was developed and evaluated with the experimental impactor drop test of pear fruits in order to identify bruises. The FE model was validated with the experimental model, resulting in low error values not exceeding 4% and 26% for internal impact energy and bruise susceptibility, respectively. Furthermore, the energy activity summary of explicit dynamics-based simulations can be an indicator for assessing the accuracy of the FE model [7,12]. Energy activity, including internal, kinetic, hourglass, and contact energy of the pear fruit drop impact, are illustrated in Figure 13. Internal energy is transferred to kinetic energy at the beginning of impact; then, kinetic energy starts to decline and is transferred to internal and contact energy at the highest impact point. Hourglass energy, also called zero-mode energy, is a deformation that does not produce volume or strain change in hex/quad meshes in a finite element model. The literature suggests that hourglass energy should not exceed 5–10% of internal energy [11,33]. In our simulation scenarios, hourglass energy did not exceed 10% of internal energy values. Therefore, we can say that our FE model is considered accurate.

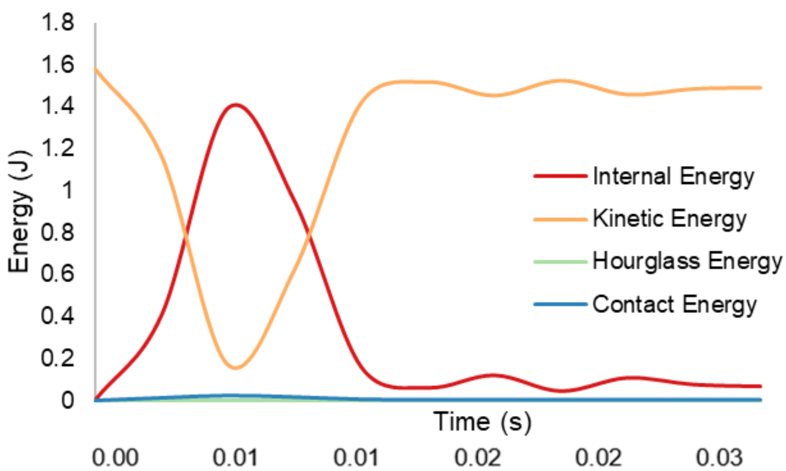

Figure 13. Energy activity summary for pear fruit drop simulation.

The FE model can be adopted to develop a packaging structure for pear fruits in order to minimize fruit bruises and protect them from mechanical damage. The proposed design is made of recycled PET plastic, which is spiral-shaped and can absorb the energy of pear fruit at impact drops. Design experiments and response surface methodology were performed to study the influence of spring design parameters on pear fruit bruise susceptibility and behavior. According to RSM results, it was found that spring pitch and thickness have a significant impact on fruit bruises compared with a number of spring revolutions. An optimal design was proposed, proving its ability to reduce bruises of fruit, comparing it to freely dropping a pear fruit on the floor.

The proposed packaging design considered the following aspects:

- Sustainability: The design proposed is made up of 3D printed recycled PET water bottles plastic, which helps achieve a circular economy and reduce greenhouse gas emissions [34]. Furthermore, the design is not disposable, and consumers can reuse the packaging. This would narrow and close loops in the supply chain.
- Physical design considerations: The design allows for ventilation thanks to its spring-based design, where air is permitted so that the quality of fruit is assured and shelf-life is extended [35]. Also, the spring feature of the design would help in absorbing shocks and vibrations due to impact forces in post-harvest logistics. Moreover, the nature of spring geometry is flexible, and spring can be extended to some extent, allowing different pear fruit sizes to be packaged. Therefore, the proposed design considers fruit shape and size adaptation.
- Mass scale production: The proposed design can be extended to be used as a modular design to make up a full packaging container as suggested in Figure 14. Each unit cell is 3D printed separately, and all units will be attached. The proposed pear fruit packaging container would serve as an integrated solution for fruit bulk packaging, retailers, and customers [36].

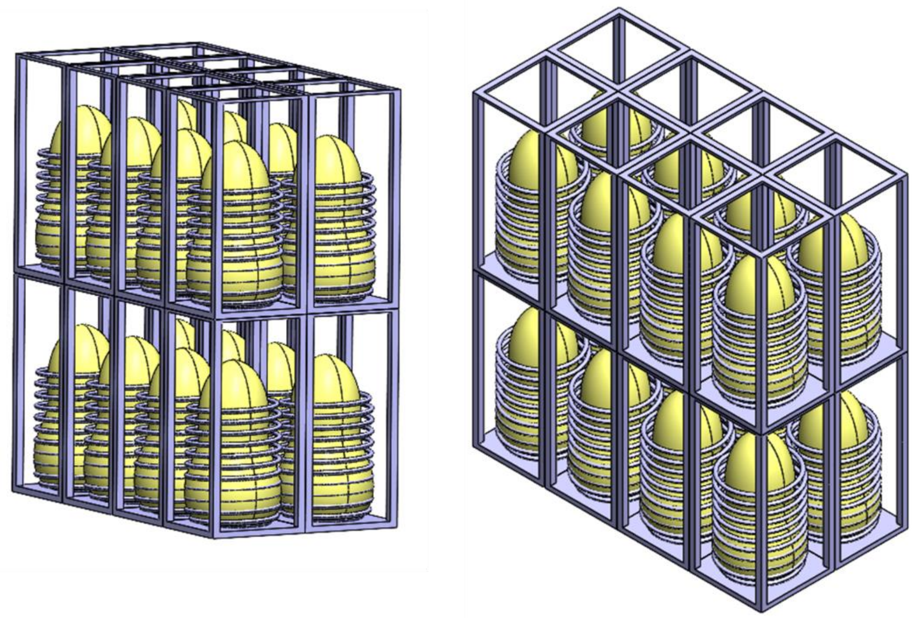

Figure 14. Proposed potential fruit packaging container.

Practical Implications

The adoption of recycled PET-based fruit packaging is considered a promising practice based on this study's results and findings. However, current practices and technology readiness aspects have to be considered in order to adopt recycled PET-based packages. For instance, processing the recycled plastic to transform it into a 3D printing filament may impose a challenge, as some issues may arise in getting continuous and consistent diameters of filaments. The material properties of recycled PET and 3D printability need to be considered to meet the specific requirements of fruit packaging. Furthermore, the design of optimal and customized packaging alternatives needs to fit various fruits and vegetables of different sizes. To speed up the development of PET-based packages, the implementation of simulation and FEA tools to assess the performance of packages under various loading conditions is needed.

By taking the above-mentioned aspects into consideration, companies and organizations can effectively transition to the use of recycled 3D printed PET for pear fruit packaging, aligning with technological advancements, environmental sustainability, and market trends. This approach does not only improve packaging performance but also enhances the overall sustainability of the post-harvest supply chain.

5. Conclusions

This work developed a pear-shaped FE model that was verified with an experimental model for impact tests in order to assess the bruise susceptibility of pear fruits. Simulated results have matched experimental results, yielding acceptable error values. By utilizing the validated pear fruit FE model, a spiral-shaped packaging design was proposed in order to absorb mechanical energy generated due to impact forces and loading. To qualitatively assess pear fruit spring behavior and to study the influence of spring design parameters (pitch, diameter, and revolutions) on bruise susceptibility, a design of experiments and response surface method were developed.

Based on RSM results, a variable pitch design attached to a thin rectangular base was proposed. The proposed design has the potential to reduce the pear fruit bruises to half (50%). The design has identical unit cells and, therefore, can be extended to be used as a packaging container for pear fruits during post-harvest transportation and logistics. Furthermore, we propose the use of recycled PET plastic water bottles to 3D print this design, providing lower manufacturing costs, reducing environmental impacts, and achieving a circular economy. The proposed spiral design is reusable and recyclable and can be assembled and disassembled according to customer or retailer preferences.

This study is exploratory, where we have explored through FEA pear fruit bruises susceptibility and recycled PET package design and modeling in order to validate the results before proceeding to the next stage of utilizing materials and energy. Extending this work to 3D manufacture the proposed design and experimentally test its performance in terms of drop impact to compare it with FEA methods would improve the result's accuracy and reliability by validating the FEA predictions. The proposed modular packaging design in this paper is conceptual, and it can be further refined, optimized, and tested experimentally and through FEA to prove its efficiency in protecting fresh produce from bruises. Furthermore, to enhance the robustness of our study, future research could include a broader range of pear fruit varieties to comprehensively assess the pear fruit's susceptibility to damage. This research offers valuable insights for ease of fruit packaging to extend fresh produce shelf-life and serves as a theoretical framework for predicting and evaluating pear fruit bruise susceptibility using finite element analysis.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

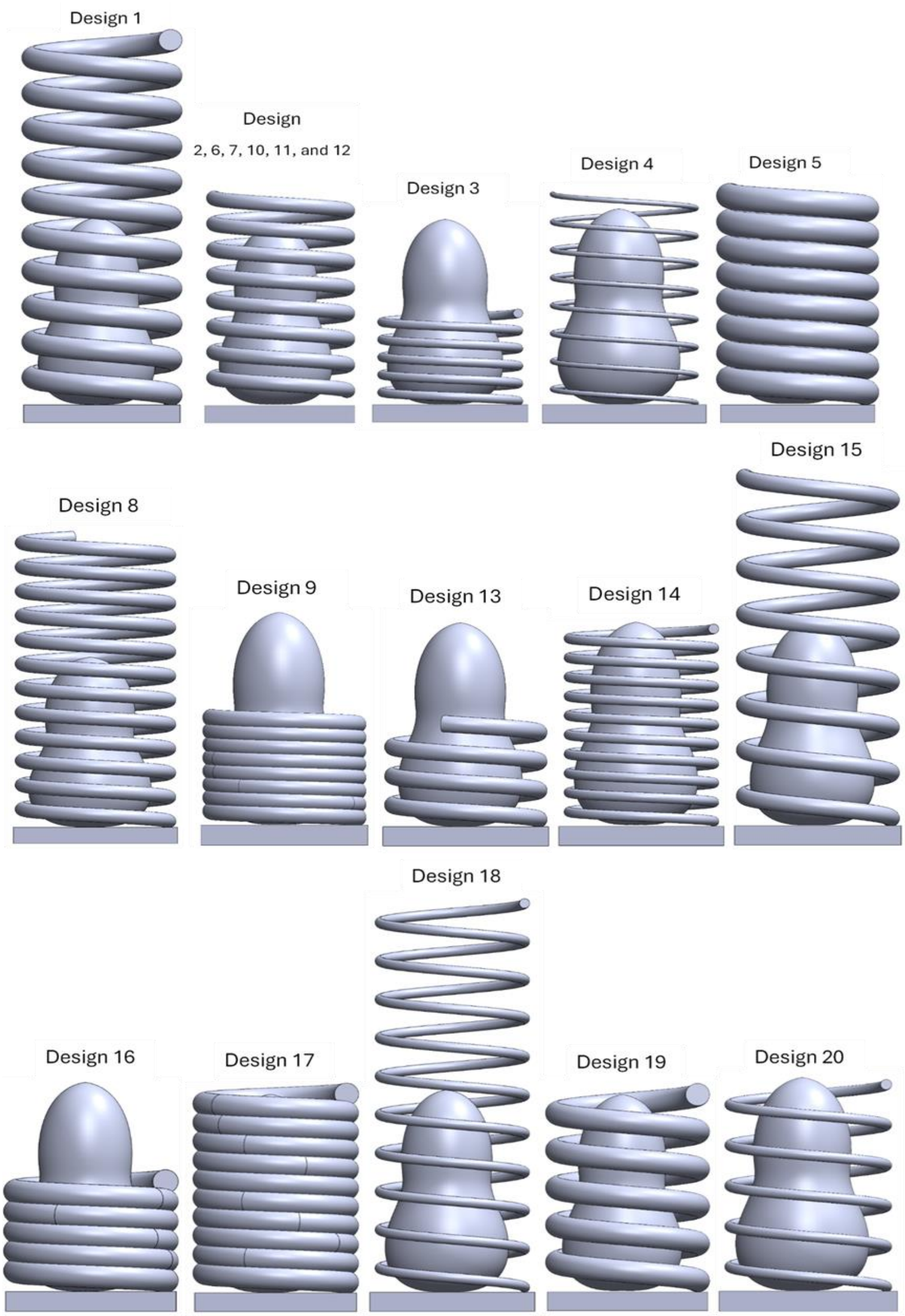

Figure A1. Generated design combinations according to CCD design of experiments.

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