Penerbit Akademia Baru

Journal of Advanced Research Design

Journal homepage:
https://akademiabaru.com/submit/index.php/ard
ISSN: 2289-7984

Evaluation of Egg Packaging Cushioning Systems Implemented with Lean Design Principles

Mohd Shahir Yahya[1,*], Mahmod Abd Hakim Mohamad[1], Nurfarahin Onn[2], Nur Fariza Abdul Aziz[3], Abdullah Wagiman[1], Muhammad Akmal Abdul Halim[4], Winardi Sani[5]

[1] Sustainable Product Development (S-ProuD), Centre for Diploma Studies, Universiti Tun Hussein Onn Malaysia (Pagoh Campus), Pagoh Education Hub, Km 1, Jalan Panchor, 84600 Panchor, Johor, Malaysia
[2] Koperasi RT Johor Zon Selatan Berhad, Jabatan Perpaduan Negara dan Integrasi Nasional Johor, Tingkat 20, Bangunan KWSP, Jalan Dato' Dalam, 80000 Johor Bahru, Johor, Malaysia
[3] Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia (Pagoh) Campus, Pagoh Education Hub, Km 1, Jalan Panchor, 84600 Panchor, Johor, Malaysia
[4] Department of Aeronautical Engineering Technology, Faculty of Mechanical & Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia (Main Campus), 86400 Parit Raja, Batu Pahat, Johor, Malaysia
[5] Universitas Sangga Buana, Bandung, Indonesia

ARTICLE INFO

Article history:
Received 20 January 2025
Received in revised form 14 February 2025
Accepted 23 May 2025
Available online 2 June 2025

Keywords:
Egg; cushion packaging; lean design; free-fall drop test

ABSTRACT

Proper packaging is critical to ensure safe and efficient distribution in the egg industry. Packaging systems must be designed to meet safety standards and customer requirements. This study focuses on evaluating the performance of cushion packaging for eggs using the lean design approach to select the most suitable packaging method. Given the fragility of eggs, which are highly susceptible to damage from impacts and surfaces, the study compares the effectiveness of three cushioning materials: polyethylene terephthalate (PET), high-impact polystyrene (HIPS), and moulded pulp cartons. Free-fall tests were conducted at various heights and orientations (flat top and flat bottom), with peak acceleration (GP) data recorded using an accelerometer and displayed via TP3 software. The results indicated that moulded pulp cartons outperformed PET and HIPS in vibration resistance and durability, maintaining product integrity even at a maximum height of 5.5 ft. The findings suggest that moulded pulp cartons offer the best cushioning solution, thanks to their excellent energy absorption properties, minimizing the risk of product damage during transport.

1. Introduction

There's a growing and widespread demand for eggs due to their high nutritional content [1]. However, eggs are delicate products, particularly vulnerable to damage during storage, transportation, and distribution, resulting in significant economic losses. Factors such as loads, mishandling, and vibrations contribute to the cracking and breakage of eggs [2]. Hence, assessing the product's fragility and sensitivity is essential to evaluate the packaging cushioning's effectiveness before selecting appropriate packaging materials [3-5]. By having a thorough awareness of the

* *Corresponding author*
E-mail address: shahir@uthm.edu.my

https://doi.org/10.37934/ard.133.1.7079

problems that need to be solved, lean design thinking may be utilized to create creative solutions that satisfy user needs by prioritizing innovation generation through customer-centric development, mainly through the development and testing of minimum viable products (MVPs) following accepted scientific methods [6,7].

Implementing egg packaging in the packaging industry is essential and warrants careful consideration. This is crucial as it can result in the development of an effective packaging system that is not only potentially safe but also reasonably priced and user-friendly [8]. Specific requirements and market objectives guide the innovation and evolution of packaging systems. A reliable and secure packaging system can minimize egg damage, particularly for export and import operations, thereby mitigating economic losses [9]. Establishing a solid partnership between transport companies and firms is essential to facilitate sharing innovations in packaging systems to prevent product failures or egg damage. A robust packaging system is pivotal in shielding the product from various threats and minimizing potential damage. Accuracy in the selection process of the packaging system is imperative to ensure it fulfils its intended function and application effectively.

The characteristics of packaging materials should include mechanical strength, optical clarity, chemical resistance, and heat tolerance [10-12]. However, these properties are also influenced by container design, product requirements, manufacturing techniques, and their environmental impact. Packaging design should align with both universal standards and user preferences. A well-designed, high-quality packaging system meets product specifications, simplicity, and user needs.

Research by Azzi *et al.,* [13] indicated that several measures must be assessed and taken regarding cushioning to promote its widespread adoption as a material for new packaging. This study identified five crucial factors within a comprehensive framework that require attention and consideration when developing a new cushioning system. These encompass safety, marketing and communication, logistics, sustainability, and ergonomics.

Choosing the appropriate packaging material is of utmost importance and a primary consideration as it serves the purpose of the distribution and storage process, which marks the culmination of the packaging journey. It is widely understood that the effectiveness of a packaging system is largely determined by its performance during distribution and storage. Hence, numerous essential characteristics and properties must be carefully considered to achieve an optimal packaging system [14]. These critical attributes include the packaging's ability to withstand climatic factors, vibrations, and impact, significantly influencing product integrity [15].

Eggs are delicate, making them prone to breakage and highly sensitive [16]. As mandated by industry standards, eggs' exportation, shipping, distribution and storage processes necessitate a well-suited packaging system to minimize damage. Without proper packing cushioning, many eggs are at risk of breakage during these processes. Furthermore, the journey involved in transportation can subject the products to strong shocks, vibrations, and mechanical impacts, leading to potential product failures [17]. Conducting free-fall test aids to identify suitable packaging cushioning. Therefore, it is imperative for industry stakeholders to continually enhance the performance and quality of existing packaging systems to ensure the safe delivery of eggs to consumers [3].

The study's objectives are twofold: firstly, to assess the efficacy of various egg packaging cushion systems currently accessible in the market, and secondly, to suggest the appropriate type of egg suspension system, along with its ideal height for conducting free-fall tests. This study aims to identify and evaluate the available egg packaging systems in the market to determine the most effective option through conducting free-fall tests. These tests simulate the conditions of transporting eggs during distribution, storage, exportation and delivery processes. Understanding the factors contributing to egg damage, particularly during implementation, can assist the industry in making informed decisions regarding packaging materials selection. The findings of this study are anticipated to guide the selection of the most optimal product packaging system.

2. Methodology

This section discusses the study's methodology that is carried out at the packaging laboratory in Universiti Tun Hussien Onn Malaysia to achieve its objectives. This study conducted the free-fall test on chicken eggs where three different materials – polyethylene terephthalate (PET), high impact polystyrene (HIPS), and moulded pulp cartons – with varying fall height values at the flat top and flat bottom orientations are compared. Furthermore, this test identified the package cushioning system's best performance and most optimal packaging material.

2.1 Preparation of the Package Cushioning Samples

Three different types of package cushioning are required to perform the free-fall test: PET, HIPS and moulded pulp carton. Figure 1 presents the models of the various package cushioning materials used in this study.

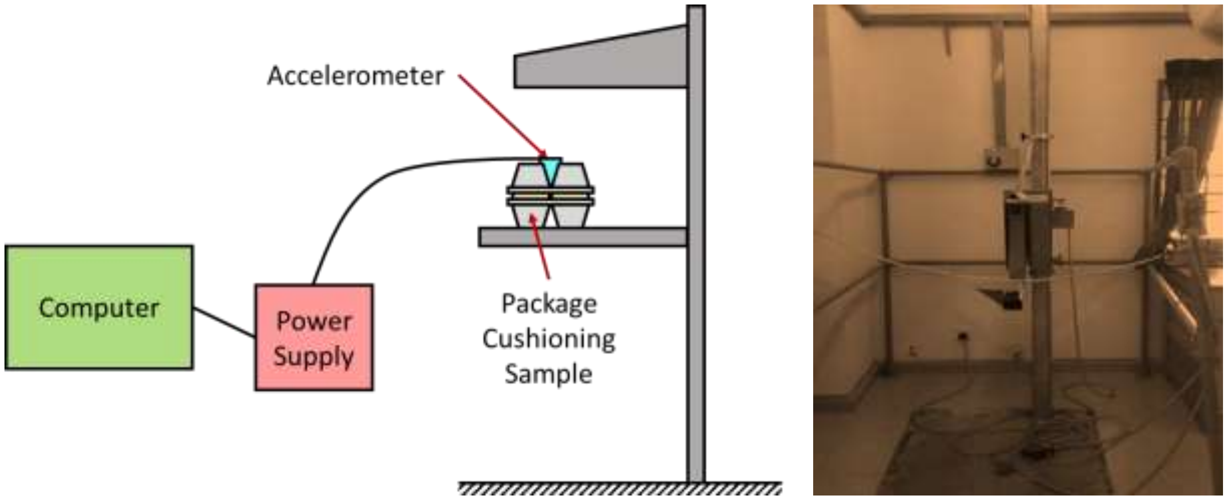
(a) (b) (c)

Fig. 1. Types of package cushioning (a) Polyethylene Terephthalate (PET) (b) High Impact Polystyrene (HIPS) (c) Moulded pulp carton

2.2 Free-Fall Test

Based on the packaging requirements, the free-fall test involves dropping a sample to determine its resistance to failure, i.e., whether it breaks or leaks as required to produce the container through proper transport specifications.

This study will use a LAB Drop Tester Model AD-100 Design Series 4410. This test procedure for this drop test is referred to as the ASTM D 5276 – Drop Test of Loaded Containers by Free-Fall (1998) [1], which can be used with the accelerometer and system analyzer from Test Partner 3 (TP3) software. The surrounding factors that need to be considered are flat and hard surfaces made of concrete or stone. If the surface falls on a steel plate, it must have a thickness of at least 13mm. During the experiment, strict handling is required to ensure no risks to the experimenter or other people.



(a) (b)

Fig. 2. Drop tester equipment (a) Schematic diagram (b) Machine

Peak acceleration (G) is sought to determine the degree of fragility or breakage of objects when experiencing shock for the product to be cushioned. An object will break or be damaged when acted upon by a force higher than the structure [2]. The formula for finding the value of G is as in Eq. (1),

$$G=\frac{\text{Predicted acceleration}}{\text{Gravity acceleration}} \tag{1}$$

Where, G is the peak acceleration or critical acceleration.

The classification of the G factor can be shown in Table 1. The packages with high G factor classification can withstand shock forces and have a low risk of falling damage.

Table 1
Classification of G factor values [19]

G Factor Value	Classification	Examples
15 – 25 G	Extremely Fragile	Precision instruments, the first generation of computer hard drives
25 – 40 G	Fragile	Benchtop and floor-standing instrumentation and electronics
40 – 60 G	Stable	Office equipment, cash registers, desktop computers
60 – 85 G	Durable	Televisions, appliances, printers
85 – 110 G	Rugged	Power supplies, machinery, monitors
110 G	Portable	Laptops, optical readers
150 G	Hand Held	Telephones, radios, calculators, microphones

Free-fall test procedures were carried out in the packaging laboratory as shown in Figure 3. Based on this figure, a sample for each cushioning is prepared first. Second, the platform of the free-fall machine is adjusted based on the required height. Then, the sample is placed on the platform with the accelerometer in good condition. After that, the height and weight data are filled once the computer is turned on. Finally, the computer software recorded the data of the dropped samples.

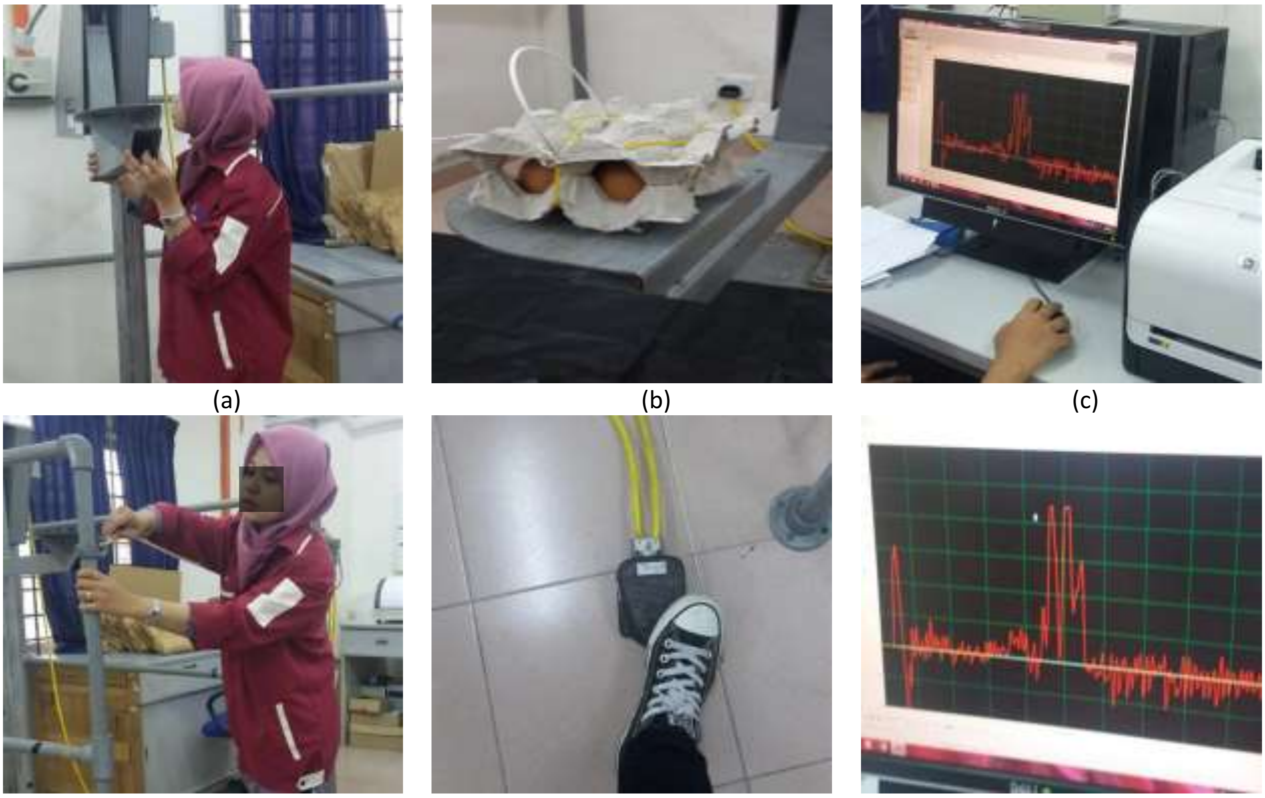


Fig. 3. Free-fall test procedures (a) Adjustment of the platform based on the required height (b) The sample is placed on the platform (c) Parameters are entered into the computer (d) The security fence is closed (e) The sample is dropped by pressing the power supply (f) Data is recorded using computer software

3. Results

This section presents the test results and findings obtained from free-fall tests conducted using a free-fall machine to evaluate various package cushioning samples with different heights and orientations. Following this test, all the data results of the peak acceleration (GP) from the free-fall test will be recorded, plotted, and analyzed to select the best material type of packaging system among the study samples.

Table 2 shows the GP results for flat top and flat bottom orientations. Referring to this table, the product with the PET cushioning system on the flat top orientation completely broke at 3.5 ft, stopping the GP values at 4.5 ft and 5.5 ft from being read. For the flat bottom orientation position, the product with the PET cushioning system obtained GP values at 1.5 ft and 2.5 ft only. Therefore, there is no value for the GP for the heights of 3.5 ft, 4.5 ft, and 5.5 ft since this product with the PET cushioning system is broken at the height of 2.5 ft.

Both products with HIPS cushioning systems on the flat top and flat bottom orientations were completely broken at 4.5 ft, where they failed to absorb shock well. As a result, no data was obtained at a height of 5.5 ft. Compared to PET and HIPS, the moulded pulp cushioning system could take the GP readings up to 5.5 ft tall without damaging the product. It shows that this material can absorb shocks well.

Table 2
Free-fall test data for three types of cushioning systems

Orientation	Height (ft)	Peak Acceleration, G_P (G)		
		PET	HIPS	Moulded pulp
Flat top	1.5	55.31	61.35	87.74
	2.5	72.93	91.31	56.56
	3.5	89.59	87.63	81.31
	4.5	-	85.80	91.45
	5.5	-	-	91.90
Flat bottom	1.5	76.86	89.92	56.02
	2.5	91.30	89.88	90.75
	3.5	-	91.70	82.86
	4.5	-	91.14	89.74
	5.5	-	-	90.09

Figures 4 and 5 present the plotted data from Table 2 for flat top and flat bottom orientation positions respectively. Based on these figures, PET cushioning has experienced the earliest total damage to the product at the height of 4.5, followed by HIPS cushioning at 3.5 ft. As previously stated, the moulded pulp cushioning system still did not damage the products at the height of 5.5 ft.

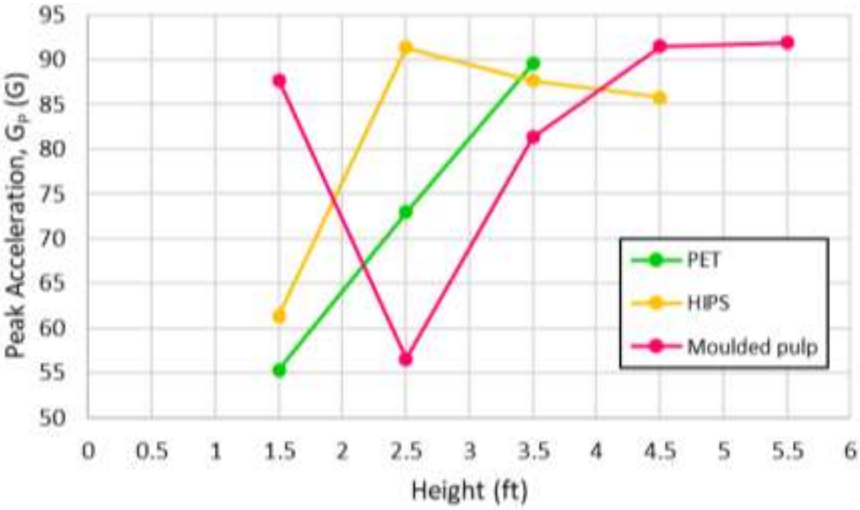


Fig. 4. The graph of peak acceleration (GP) vs. height for flat top orientation position

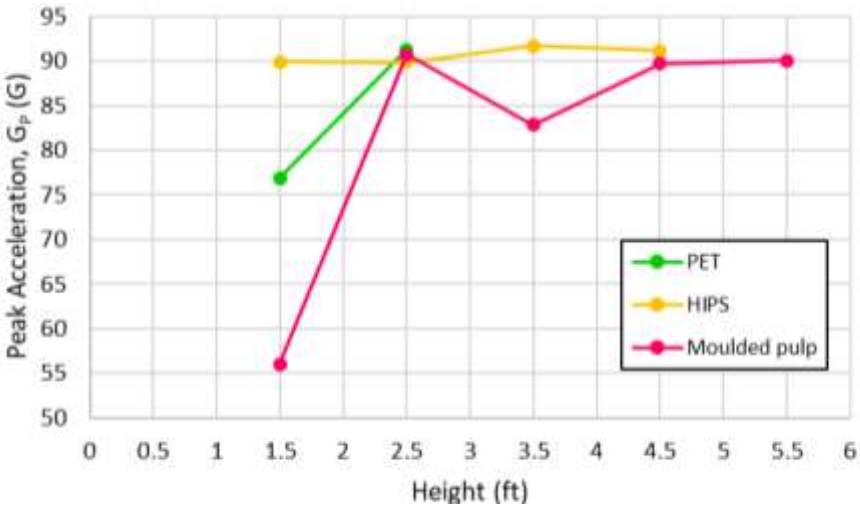


Fig. 5. The graph of peak acceleration (GP) versus height for flat bottom orientation position

4. Discussion

The packaging system is the most crucial part of the product protection process. When a product is dropped, a shock may cause damage. Good materials for the packaging system will absorb shocks [11]. In this project, falling happens when handling eggs in the product distribution system. Since eggs are so sensitive, any that fall during the handling procedure will break and cannot be used again.

Furthermore, careless handling can damage the eggs during the delivery process. In addition, while the eggs are being transported, several factors such as vibrations and shocks from the vehicles' movement on uneven roads when they stop or start, can cause the eggs to experience a shock force that could break them. Therefore, the packaging system can absorb the vibrations and shocks during operations on the floor, pallets, trucks or other packages in the warehouse.

A free-fall test is performed in this study to identify the ideal materials for the egg package cushioning system based on their performance in ensuring the safe delivery of the eggs to consumers. A good cushioning system will ensure the product is secure when it reaches the consumer. Therefore, a product's fragile and sensitive characteristics must be determined to evaluate the packaging cushion's performance before it is used as a reference for selecting packaging materials.

The properties of the material used to package eggs significantly impact its application. Furthermore, these properties need to be emphasized to prevent an increase in the percentage of products failing due to inefficient packaging systems. The strength of a packaging material is an important factor in the use of a packaging system. The GP value is a parameter used to determine the ability of the cushioning material.

From the results, moulded pulp cartons were considered ideal for packaging for several reasons,

i. Sustainable: Moulded pulp is typically made from recycled materials, making it eco-friendly. It is biodegradable and compostable, reducing environmental impact [18].
ii. Protective: Moulded pulp provides cushioning and protection for delicate items during shipping and handling. It can absorb shocks and vibrations, keeping products safe [19].
iii. Customizable: Moulded pulp can be moulded into various shapes and sizes to fit specific products. It is versatile and can accommodate different packaging needs [20].
iv. Cost-effective: Moulded pulp is often cost-effective compared to other packaging materials like plastics. It can be produced efficiently and at a lower cost [20].
v. Lightweight: Moulded pulp is lightweight, which can help reduce shipping costs and carbon footprint. It is also easy to handle and transport [19,20].

Therefore, the combination of sustainability, protection, customization, cost-effectiveness, and lightweight nature makes moulded pulp cartons an ideal packaging material for various products.

Recent developments in materials science have introduced smart materials and nanomaterials that can revolutionize packaging systems [21]. These materials, with unique properties such as shape-memory alloys or nanocomposites, could absorb and dissipate energy more efficiently than conventional moulded pulp. Incorporating materials with programmable elasticity and self-healing features could mitigate damage even during severe impacts, ensuring the eggs remain unbroken during transport. Furthermore, advancements in biodegradable polymers could merge sustainability with higher protective capabilities, reducing the need for compromise between eco-friendliness and performance.

By embedding sensors into the packaging, companies can now monitor real-time conditions such as temperature, humidity, shock, and vibration [22]. These sensors can alert supply chain managers if eggs are exposed to harmful conditions, allowing for proactive measures to prevent spoilage or damage. Internet of Things (IoT) technology makes it possible to track the exact moments and locations where damage or mishandling occurs, facilitating data-driven improvements in the packaging and distribution process. Advanced shock sensors and accelerometers could even assist in quality assurance by providing data on the magnitude and duration of impacts during transit, helping companies fine-tune packaging designs based on actual distribution environments.

Advanced computational tools such as Finite Element Analysis (FEA) and other simulation models can predict how various packaging designs perform under different stress conditions. These models enable engineers to simulate the effects of shocks, vibrations, and free-falls, minimizing trial-and-error approaches [23]. This accelerates the design process and ensures that the cushioning materials selected are optimized for specific real-world conditions, such as vehicle movement over uneven roads or careless handling during loading and unloading. Moreover, artificial intelligence (AI)-driven simulations can iteratively improve designs by learning from historical shipping data, reducing the time and cost of packaging development.

Lean design principles emphasize minimizing waste and maximizing efficiency. 3D printing technologies can now be leveraged to produce customized packaging solutions for eggs, optimizing the size, shape, and cushioning features for the exact needs of the product [24]. This method eliminates the excess material often associated with traditional manufacturing techniques, resulting in packaging using fewer resources while offering superior protection. The precision of 3D printing allows for highly tailored designs that can adapt to specific distribution environments or consumer requirements.

Automation technologies, such as robotics and AI, can improve the consistency and quality of packaging processes [25]. Automated packaging systems equipped with machine learning algorithms can adjust the amount and type of packaging material used in real-time, depending on factors like the product’s fragility or the expected transportation conditions. This flexibility ensures that each batch of eggs is packed with the optimal cushioning, reducing waste and the likelihood of product damage. In addition, robotic systems can handle eggs with more precision and care than human workers, further reducing the risk of breakage due to mishandling.

While moulded pulp cartons are already a sustainable option, advancements in circular economy practices could take this even further. Companies could implement systems to recover and recycle packaging materials at the end of their life cycle, using technology to track and manage the return of used cartons. New materials made from organic waste or algae-based biopolymers are also being explored, potentially creating even greener alternatives to moulded pulp without sacrificing durability or protection. The integration of blockchain technology can help ensure transparency and traceability in the recycling process, allowing consumers and companies to verify the sustainability claims of their packaging.

Incorporating these advanced technologies into egg packaging systems would improve egg protection and handling and align with sustainability and operational efficiency goals. As companies continue to adopt Lean design principles, leveraging these innovations can significantly reduce waste, energy consumption, and costs while ensuring the safe delivery of products.

5. Conclusions

In conclusion, this study has achieved its objective, which is to evaluate the performance of various existing egg package cushioning systems through free-fall tests at different heights and orientation positions by considering lean design. Furthermore, determining the ideal packaging system can prevent a product from being damaged during delivery. It was found that the best material for the package cushioning system in this study is the moulded pulp carton because there is no broken egg at the maximum height of 5.5 ft. This material has good energy absorption, thus being able to prevent the egg from experiencing breaks during the distribution process.

The following recommendations are considered in the next research on egg package cushioning systems:

i. Carry out the experiments on other orientation positions, such as the upper edge, transverse edge, upper corner and lower corner orientations, to identify the G_P values of different orientations.
ii. Perform the experiments using the same material of the package cushioning system but different thicknesses.
iii. Conduct the experiments using different materials of the package cushioning systems but same thickness.
iv. Carry out the tests using another type of cushioning material to observe their capabilities.
v. Perform the tests in real situations during the distribution and storage processes in vehicles or warehouses.
vi. Conduct the vibration tests for the egg cushioning system when a vehicle (e.g., a truck) is moving.
vii. Design and develop a new package cushioning system to replace the existing egg cushioning system.

Acknowledgement
This research was funded by Universiti Tun Hussein Onn Malaysia (UTHM) through the Human Capital Development Unit management of the UTHM Registrar Office. The authors would also like to thank the Centre for Diploma Studies, UTHM for its support.

References
[1] Jianguo, Zhang, Wang Fang, Yang Shugang, Zhang YiNong, Song Haiyan, and Li Maoting. "Analysis of Drop Impact Behaviour of Eggs with Different Drop Height and Cushion Materials." In *AASRI International Conference on Industrial Electronics and Applications (IEA 2015)*, pp. 36-39. Atlantis Press, 2015. https://doi.org/10.2991/iea-15.2015.10
[2] Donofre, Ana Carolina, Iran José Oliveira da Silva, Aérica Cirqueira Nazareno, and Iuri Emmanuel de Paula Ferreira. "Mechanical vibrations in the transport of hatching eggs and the losses caused in the hatch and quality of broiler chicks." *Journal of Agricultural Engineering* 48, no. 1 (2017): 36-41. https://doi.org/10.4081/jae.2017.593
[3] Chowdhury, E. U., and A. Morey. "Intelligent packaging for poultry industry." *Journal of Applied Poultry Research* 28, no. 4 (2019): 791-800. https://doi.org/10.3382/japr/pfz098
[4] Yang, Xiaojun, Huoxing Li, Ying Sun, Yijie Cai, Hongdi Zhou, and Fei Zhong. "Research on the Design Method of Cushioning Packaging for Products with Unbalanced Mass." *Applied Sciences* 13, no. 15 (2023): 8632. https://doi.org/10.3390/app13158632
[5] Mertens, Kristof, Flip Bamelis, Bart Kemps, B. Kamers, Eva Verhoelst, Bart De Ketelaere, M. Bain, Eddy Decuypere, and Josse De Baerdemaeker. "Monitoring of eggshell breakage and eggshell strength in different production chains of consumption eggs." *Poultry Science* 85, no. 9 (2006): 1670-1677. https://doi.org/10.1093/ps/85.9.1670
[6] Dobrigkeit, Franziska, Danielly de Paula, and Matthias Uflacker. "InnoDev: a software development methodology integrating design thinking, scrum and lean startup." In *Design Thinking Research: Looking Further: Design Thinking Beyond Solution-Fixation*, pp. 199-227. Cham: Springer International Publishing, 2018.
[7] Mansoori, Yashar, and Martin Lackéus. "Comparing effectuation to discovery-driven planning, prescriptive entrepreneurship, business planning, lean startup, and design thinking." *Small Business Economics* 54 (2020): 791-818.
[8] Ghaani, Masoud, Carlo A. Cozzolino, Giulia Castelli, and Stefano Farris. "An overview of the intelligent packaging technologies in the food sector." *Trends in Food Science & Technology* 51 (2016): 1-11. https://doi.org/10.1016/j.tifs.2016.02.008
[9] Versino, Florencia, Florencia Ortega, Yuliana Monroy, Sandra Rivero, Olivia Valeria López, and María Alejandra García. "Sustainable and bio-based food packaging: A review on past and current design innovations." *Foods* 12, no. 5 (2023): 1057. https://doi.org/10.3390/foods12051057

[10] Shah, Yasir Abbas, Saurabh Bhatia, Ahmed Al-Harrasi, Muhammad Afzaal, Farhan Saeed, Md Khalid Anwer, Mahbubur Rahman Khan, Muhammad Jawad, Noor Akram, and Zargham Faisal. "Mechanical properties of protein-based food packaging materials." *Polymers* 15, no. 7 (2023): 1724. https://doi.org/10.3390/polym15071724

[11] Narushin, Valeriy G., Mykola G. Chausov, Larysa V. Shevchenko, Andriy P. Pylypenko, Viktor A. Davydovych, Michael N. Romanov, and Darren K. Griffin. "Shell, a naturally engineered egg packaging: Estimated for strength by non-destructive testing for elastic deformation." *Biosystems Engineering* 210 (2021): 235-246. https://doi.org/10.1016/j.biosystemseng.2021.08.023

[12] Şahansoy, Hakan, Cengiz Caner, and Muhammed Yüceer. "The shellac and shellac nanocomposite coatings on enhanced the storage stability of fresh eggs for sustainable packaging." *International Journal of Biological Macromolecules* 261 (2024): 129817. https://doi.org/10.1016/j.ijbiomac.2024.129817

[13] Azzi, Anna, Daria Battini, Alessandro Persona, and Fabio Sgarbossa. "Packaging design: general framework and research agenda." *Packaging technology and science* 25, no. 8 (2012): 435-456. https://doi.org/10.1002/pts.993

[14] Boz, Ziynet, Virpi Korhonen, and Claire Koelsch Sand. "Consumer considerations for the implementation of sustainable packaging: A review." *Sustainability* 12, no. 6 (2020): 2192. https://doi.org/10.3390/su12062192

[15] Lin, Menghua, Olaniyi Amos Fawole, Wouter Saeys, Di Wu, Jun Wang, Umezuruike Linus Opara, Bart Nicolai, and Kunsong Chen. "Mechanical damages and packaging methods along the fresh fruit supply chain: A review." *Critical Reviews in Food Science and Nutrition* 63, no. 30 (2023): 10283-10302. https://doi.org/10.1080/10408398.2022.2078783

[16] Seydim, A. C., and P. L. Dawson. "Packaging effects on shell egg breakage rates during simulated transportation." *Poultry science* 78, no. 1 (1999): 148-151. https://doi.org/10.1093/ps/78.1.148

[17] Rouillard, Vincent, Matthew James Lamb, Julien Lepine, Michael Long, and Daniel Ainalis. "The case for reviewing laboratory-based road transport simulations for packaging optimisation." *Packaging Technology and Science* 34, no. 6 (2021): 339-351. https://doi.org/10.1002/pts.2563

[18] Bordón, Pablo, Daniel Elduque, Rubén Paz, Carlos Javierre, Dragan Kusić, and Mario Monzón. "Analysis of processing and environmental impact of polymer compounds reinforced with banana fiber in an injection molding process." *Journal of Cleaner Production* 379 (2022): 134476. https://doi.org/10.1016/j.jclepro.2022.134476

[19] Dislaire, Claire, Bastien Seantier, Marion Muzy, and Yves Grohens. "Mechanical and hygroscopic properties of molded pulp products using different wood-based cellulose fibers." *Polymers* 13, no. 19 (2021): 3225. https://doi.org/10.3390/polym13193225

[20] Chinga-Carrasco, Gary, Jost Ruwoldt, Eva Pasquier, Marianne Øksnes Dalheim, and Martin K. Wieser. "Development of a beverage carton closure cap based on 100% wood pulp fibres." *Journal of Cleaner Production* 445 (2024): 141339. https://doi.org/10.1016/j.jclepro.2024.141339

[21] Sani, Mahmood Alizadeh, Maryam Azizi-Lalabadi, Milad Tavassoli, Keyhan Mohammadi, and David Julian McClements. "Recent advances in the development of smart and active biodegradable packaging materials." *Nanomaterials* 11, no. 5 (2021): 1331. https://doi.org/10.3390/nano11051331

[22] Cil, Ahmet Yunus, Dini Abdurahman, and Ibrahim Cil. "Internet of Things enabled real time cold chain monitoring in a container port." *Journal of Shipping and Trade* 7, no. 1 (2022): 9. https://doi.org/10.1186/s41072-022-00110-z

[23] Fadiji, Tobi, Corne J. Coetzee, Tarl M. Berry, Alemayehu Ambaw, and Umezuruike L. Opara. "The efficacy of finite element analysis (FEA) as a design tool for food packaging: A review." *Biosystems Engineering* 174 (2018): 20-40. https://doi.org/10.1016/j.biosystemseng.2018.06.015

[24] Witek-Krowiak, Anna, Daniel Szopa, and Beata Anwajler. "Advanced Packaging Techniques—A Mini-Review of 3D Printing Potential." *Materials* 17, no. 12 (2024): 2997. https://doi.org/10.3390/ma17122997

[25] Licardo, Josip Tomo, Mihael Domjan, and Tihomir Orehovački. "Intelligent robotics—A systematic review of emerging technologies and trends." *Electronics* 13, no. 3 (2024): 542. https://doi.org/10.3390/electronics13030542