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Sustainable Packaging Solutions: Food Engineering and Biodegradable Materials

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Abstract: In modern, fast-paced lifestyles, food containers have become a popular solution for quick meals; however, they have significantly contributed to the increase in plastic packaging waste, which poses a substantial environmental risk. The prevalent use of non-biodegradable plastic containers exacerbates plastic pollution, contradicting government regulations designed to reduce plastic usage and promote sustainability. To address these issues, this study integrates TRIZ, ergonomics, inherent safety, and universal design methodologies, with an emphasis on sustainability. First, the technical contradiction matrix from TRIZ is applied to identify parameters for improvement without inducing negative side effects. Ergonomics principles ensure the development of user-friendly designs, while inherent safety and universal design approaches aim for accessibility and full biodegradability. Through a systematic innovation design process, this research proposes a biodegradable food container capable of decomposing entirely into particles and water within one month, blending naturally with the soil without compromising functionality. Moreover, the container incorporates a quick-alignment mechanism and an intuitive sealing design that ensures airtightness and spill prevention. As a result, the product not only meets user demands but also addresses pressing environmental concerns, aligning with global sustainability goals.

Keywords: biodegradable; food containers; TRIZ; ergonomics; inherent safety; universal design

1. Introduction

The widespread use of plastic food containers in modern society primarily addresses the demand for convenient and fast meals. Particularly in Asian countries, the fast-paced lifestyle and pressures from work and study have contributed to a decline in traditional home cooking, making plastic food containers an essential tool for meeting daily dietary needs. As the culture of dining out has become more prevalent, the consumption of plastic food containers has significantly increased, with many individuals opting for plastic containers when purchasing takeaway food or beverages for the convenience of immediate consumption. Although plastic food containers offer advantages in food storage and portability, they have led to a growing plastic pollution crisis, which has emerged as a major environmental issue of global concern. This increasing problem has driven consumers and businesses to seek more environmentally sustainable alternatives, focusing on reducing the negative environmental impact while continuing to meet modern dietary needs.

Recycling food containers in Asia presents challenges due to rapid urbanization and growing waste generation. While the 3R concept—Reduce, Reuse, Recycle—is promoted, its success varies. Developed nations like Japan, Singapore, and South Korea lead in waste reduction, whereas developing countries face barriers such as weak policies, low public awareness, and limited technology, hindering effective implementation [1,2]. According to data from Taiwan's Ministry of the Environment, the use and recycling of paper food containers have shown significant growth in recent years. In 2018, the recycling volume of paper food containers in Taiwan approached 40,000 metric tons, and by October 2020, this figure had risen to 140,000 metric tons. However, the recycling process for paper containers is not as straightforward as it seems. Many paper food containers are lined with a plastic coating, making the recycling process energy-intensive, and smaller recycling companies may struggle to handle these wastes effectively. Consequently, some containers are ultimately incinerated [3]. The improper disposal of paper food containers poses environmental challenges. Over time, these materials, particularly those with plastic linings, contribute to waste accumulation and increase the burden on waste management systems. This underscores the need for more sustainable and easily recyclable packaging solutions, particularly in the food industry, which generates a significant volume of disposable containers.

Biodegradable plastics, such as polylactic acid (PLA), are widely regarded as promising solutions to mitigate plastic pollution due to their ability to degrade into water and carbon dioxide under specific conditions. These plastics, often based on polyester compounds, have the ability to undergo hydrolysis and microbial degradation under appropriate conditions, eventually breaking down into water and carbon dioxide. Despite these advantages, biodegradable plastics face significant challenges in practical applications. For instance, their production costs are two to three times higher than those of conventional plastics, which limits their scalability for widespread adoption. Additionally, many biodegradable plastics, including PLA, have inherent limitations such as reduced thermal stability, softening at temperatures above 60 °C, and the requirement for controlled composting environments to achieve effective degradation [4]. These challenges underscore the need for further research into enhancing the performance and cost-efficiency of biodegradable materials.

To address the pressing environmental challenges posed by single-use food containers, this study investigates innovative solutions that leverage biodegradable materials to minimize environmental impact without compromising functionality. The research hypothesizes that integrating TRIZ methodologies, ergonomic principles, inherent safety, and universal design approaches can lead to the development of a fully biodegradable food container that meets user needs while aligning with global sustainability goals. The primary objective is to design a container that effectively combines eco-friendliness with practicality, offering an impactful alternative to conventional plastic-based food packaging.

2. Literature Review

2.1. Market Analysis of Food Containers

The global food container market is projected to grow from USD 168.90 billion in 2023 to over USD 256.60 billion by 2033 at a compound annual growth rate (CAGR) of 4.27% during the forecast period from 2024 to 2033 [5]. The food container market, particularly the sectors of disposable and reusable containers, has garnered increasing attention. Disposable containers are highly favored for their convenience, especially in the fast-paced dining and takeaway sectors, catering to the needs of modern, on-the-go lifestyles [6]. However, with the growing emphasis on sustainable development, there is increasing demand for environmentally friendly alternatives. Reusable containers are gaining traction as sustainable options, promoting environmental protection, long-term durability, and a reduced ecological footprint. These containers attract consumers who are mindful of their environmental impact and aligned with sustainability goals. As public awareness of health, convenience, and environmental sustainability increases, the food container market is evolving towards greater diversity and eco-friendliness [7].

Plastic disposable containers continue to hold a significant share in the food packaging industry due to their versatility and wide range of applications. Common materials include polypropylene (PP) and polystyrene (PS). PP is widely recognized for its high heat resistance, making it suitable for microwavable food containers, while PS, despite softening at temperatures around 75 °C, exhibits strong cold resistance, which makes it ideal for products like ice cream [8]. However, concerns about the environmental impact, health risks, and reliance on fossil resources persist with plastic containers. Similarly, paperboard containers, made from bleached pulp board with a waterproof or oil-resistant plastic coating, pose environmental challenges if not properly recycled, contributing to pollution [9]. Although lightweight and offering versatile structural designs, paperboard containers are less durable when exposed to liquids or oils and can be easily damaged in humid environments. Moreover, their production requires considerable energy and water resources, raising further environmental concerns.

Biodegradable containers have emerged as a more sustainable trend in the food packaging industry. Made from natural plant fibers, bioplastics, or other biodegradable materials such as corn starch, bagasse, bamboo, or wood pulp, these containers decompose into glucose, eventually breaking down into water and carbon dioxide through microbial activity. Their complete biodegradability ensures no long-term environmental impact [10]. These containers are widely appreciated for their sustainability and are used for various food products, including takeout, fast food, and baked goods. Despite their environmental benefits, the higher production costs of biodegradable containers due to the use of specialized materials are a consideration that is generally acceptable to environmentally conscious consumers.

2.2. Fully Biodegradable Technology

Several technologies have advanced the formulation of biodegradable plastics, focusing on enhancing mechanical properties while maintaining biodegradability, a crucial aspect of sustainable materials development. Wu and Gao (2005) reported a graft copolymerization technique using natural starch to improve molding properties, eliminating the need for anti-sticking agents while maintaining tensile and tear strength [11]. This method enhances the polymer's side chains, ensuring mechanical integrity during processing and use while allowing the product to decompose naturally. Chen (2006) introduced a biodegradable plastic composition incorporating synthetic biodegradable polymers with ester groups in both the main and side chains, combined with modified starch and copolymers [12]. This formulation avoids conventional plastics such as PE, PP, PS, and PVC, offering a cost-effective and sustainable alternative that balances biodegradability with practical processing characteristics.

Nanocomposite technology has also been applied to enhance sustainability. Lin et al. (2011) [13] developed biodegradable materials by combining starch, water-based polyurethane, and nano-powders. The use of modified nano-powders improved the material's physical and chemical properties, creating fully biodegradable products that meet both environmental and functional standards. Chen et al. (2012) demonstrated a starch resin composed of biochemically modified starch and biodegradable polyester, producing films that comply with both European and American compostability standards (EN13432, ASTM D 6400-04) [14]. This technology provides an environmentally friendly alternative for film-based products, supporting global sustainability initiatives.

Other innovations include using thermoplastic polyurethane (TPU) blended with polylactic acid (PLA) to create biodegradable plastics, with starch as a filler to reduce production costs. This blend exhibited higher tear resistance than commercially available LDPE plastic bags, showing potential for broader sustainable applications [15]. Huang (2022) described a composite material using calcium carbonate, cellulose acetate, and other mineral particles, offering both environmental and antimicrobial benefits. These readily available raw materials result in durable products that resist brittleness and cracking [16].

In food packaging, several biodegradable solutions have emerged, aligning with sustainability goals. One case utilized biodegradable paper with a waterproof coating to create a fully compostable food container, though the design lacked practical appeal [17]. Another technology used PLA through injection molding to produce containers capable of withstanding temperatures above 100 °C, which decompose into water and carbon dioxide under composting conditions, contributing to soil enrichment. Lin (2018) developed edible utensils made from powdered food ingredients, which are baked into shape. These utensils can either be consumed or fully decomposed by bacteria, offering an innovative solution for reducing waste and promoting environmental sustainability [18].

2.3. TRIZ Method

TRIZ, a methodology for inventive problem-solving, has been widely applied in product development and innovation across various industries, underscoring its significance in achieving competitive and sustainable outcomes in business [19]. At its core, TRIZ provides a systematic approach to solving problems by eliminating trade-offs that typically constrain conventional problem-solving methods. Its key tools include the contradiction matrix, which helps identify conflicts between design parameters, 39 engineering parameters, 40 inventive principles, problem hierarchy analysis (PHA), nine-window thinking, substance-field analysis, 76 standard solutions, ideal final result (IFR), and the ARIZ method, a step-by-step algorithm for solving complex problems [20,21].

In recent years, research has successfully integrated TRIZ with the Total Quality and Innovation Management for Healthcare (TQIM-H) framework, creating a robust approach for healthcare professionals to design innovative solutions while adhering to stringent medical guidelines. For example, when addressing challenges in medical device design, TRIZ's contradiction matrix can be employed to pinpoint conflicting requirements, such as ensuring both durability and lightweight properties. These conflicts are then addressed using inventive principles, followed by validation within the TQIM-H framework to ensure both innovation and regulatory compliance [22].

Moreover, TRIZ has been instrumental in promoting sustainable development and eco-friendly product design. By optimizing energy efficiency, reducing material waste, and developing products that align with the Sustainable Development Goals (SDGs), TRIZ enables designers to create sustainable innovations that meet both consumer demands and environmental requirements. Its use of the contradiction matrix and standard solutions helps designers navigate the complex balance between environmental protection and product performance, making it an indispensable tool for green design and reducing carbon footprints in line with global sustainability efforts [23–30].

2.4. Ergonomics

Ergonomics studies human interaction with work environments, aiming to optimize systems for human physiological and psychological needs. By enhancing efficiency, safety, and comfort, ergonomics supports sustainability by reducing user strain and prolonging the lifespan of both workforce and equipment. Techniques like human–machine systems analysis, anthropometry, and cognitive studies are employed to achieve these goals [31–33].

A central principle is designing systems that enhance human well-being and performance, which is crucial for sustainable product and workspace design. This minimizes resource waste while maximizing user satisfaction and functionality. Continuous evaluation of human-machine interactions ensures solutions meet technical and sustainability requirements, emphasizing human-centered design [34].

2.5. Inherent Safety

Inherent safety focuses on addressing hazards at their source, fundamentally reducing risks, and aligning with sustainability goals. By incorporating design measures to eliminate or control risks, it minimizes accidents, human injury, and property damage while reducing material waste and energy use [35–37].

Key strategies include material selection, structural optimization, and mechanical principles to enhance safety. Approaches such as foolproof design, simplification, and effective process control through automation and monitoring prevent accidents and ensure rapid responses to abnormal conditions. Early integration of these principles improves design efficiency and sustainability, complemented by proper training and safety management [38–41].

2.6. Universal Design

Universal Design (UD) ensures products, systems, and environments are accessible and user-friendly for diverse populations, minimizing the need for costly adaptations. By aligning with sustainability objectives, UD promotes inclusivity and long-term usability through durable and adaptable designs [42,43].

Its seven principles—equitable use, flexibility, intuitive operation, perceptible information, tolerance for error, low physical effort, and appropriate space—enhance inclusivity while conserving resources. UD addresses diverse needs, including those of elderly and disabled individuals, fostering a more inclusive society. Its focus has evolved to remove barriers and accommodate aging populations, emphasizing consensus-driven solutions that support diverse user groups [44,45].

3. Methodology

This study primarily employed the 39 engineering parameters from the TRIZ methodology to identify the parameters to be improved and those to be avoided from the deterioration perspective. A technical contradiction matrix was then created, and the 40 inventive principles were applied for analysis. The 39 engineering parameters represent common attributes in engineering systems, such as weight, strength, temperature, and manufacturing precision, which are used to define technical contradictions in a design. For instance, in this study, parameters such as ease of operation, material weight, and reliability were identified as critical to the food container's functionality and sustainability goals. These parameters were selected based on an evaluation of user needs, environmental impact, and manufacturing constraints. A technical contradiction matrix was then created to map the selected parameters against the TRIZ 40 inventive principles, which offer strategies to resolve these contradictions. The 40 inventive principles are a set of generalized solutions to engineering challenges, such as segmentation, asymmetry, dynamicity, and self-service. A detailed summary of the 39 engineering parameters [46] and 40 inventive principles [47] is provided in Tables 1 and 2, showing their linkage and application in the design process.

Table 1. Summary of the 39 engineering parameters.

1. Weight of moving object	11. Stress or pressure	21. Power	31. Object-generated harmful factors
2. Weight of stationary object	12. Shape	22. Loss of energy	32. Ease of manufacture
3. Length of moving object	13. Stability of the object's composition	23. Loss of substance	33. Ease of operation
4. Length of stationary object	14. Strength	24. Loss of information	34. Ease of repair
5. Area of moving object	15. Duration of action by a moving object	25. Loss of time	35. Adaptability or versatility
6. Area of stationary object	16. Duration of action by a stationary object	26. Quantity of substance/the matter	36. Device complexity
7. Volume of moving object	17. Temperature	27. Reliability	37. Difficulty of detecting and measuring
8. Volume of stationary object	18. Illumination intensity	28. Measurement accuracy	38. Extent of automation
9. Speed	19. Use of energy by moving object	29. Manufacturing precision	39. Productivity
10. Force	20. Use of energy by stationary object	30. External harm affects the object	

Table 2. Summary of the 40 Invention Principles.

1. Segmentation	11. Beforehand cushioning	21. Skipping	31. Porous material
2. Tanking out	12. Equipotentiality	22. Convert harm into benefit	32. Changing the color
3. Local quality	13. Do it in reverse	23. Feedback	33. Homogeneity
4. Asymmetry	14. Spheroidality–curvature	24. Intermediary	34. Discarding and recovering
5. Merging	15. Dynamicity	25. Self-service	35. Transformation of properties
6. Universality	16. Partial or excessive actions	26. Copying	36. Phase transition
7. Nested doll	17. Transition into a new dimension	27. Cheap, short-lived objects	37. Thermal expansion
8. Anti-weight	18. Mechanical vibration	28. Replacement of mechanical system	38. Accelerated oxidation
9. Prior anti-action	19. Periodic action	29. Pneumatics and hydraulics	39. Inert environment
10. Preliminary action	20. Continuity of useful action	30. Flexible shells or thin films	40. Composite materials

Subsequently, the ergonomic design was developed using human factors engineering methods to optimize the container's usability and comfort for a diverse range of users. This involved conducting user-centered analyses to identify common handling challenges, such as grip strength and container stability during use. Specific ergonomic improvements included the incorporation of contoured handles to enhance grip and reduce strain during transportation, as well as a lightweight design to minimize physical effort, particularly for elderly users or individuals with limited hand strength. These modifications were validated through iterative prototyping and user testing to ensure both functionality and comfort. In addition, inherent safety principles were applied by addressing potential failure modes that could compromise user safety or lead to food spillage. For instance, structural reinforcements were integrated to prevent accidental collapse during handling, and the container was designed with secure locking mechanisms to minimize the risk of food contamination. Universal design principles were utilized to ensure accessibility and ease of use for users of all ages and abilities. This included features such as intuitive opening mechanisms that require minimal force and clear visual indicators to guide operation. These principles ensured that the container could be effectively operated by individuals with varying physical and cognitive capabilities, promoting inclusivity in its design. Finally, during the mechanical design phase, the structure and research outcomes of the designed product were simulated using 3D modeling through SolidWorks software (2014), as shown in Figure 1.

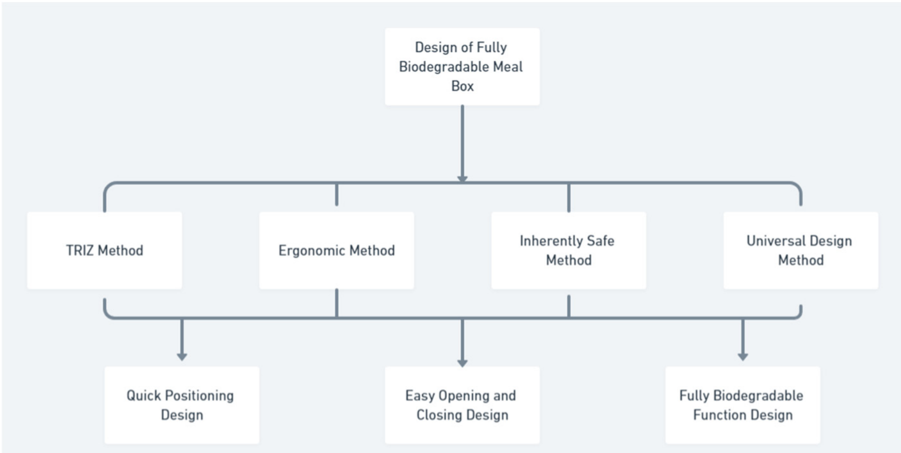


Figure 1. Conceptual Framework.

3.1. Quick Positioning Design

3.1.1. TRIZ Method for Positioning

This study employed the TRIZ contradiction matrix to design a rapid and precise alignment mechanism for food containers and lids. Improvement parameters included 06. (area of a stationary object), 27. (reliability), and 33. (ease of use), while parameters to avoid deterioration were 01. (weight of a moving object), 31. (harmful side effects), and 36. (device complexity). The results of the contradiction matrix, including corresponding inventive principles, are summarized in Table 3.

Table 3. Technical contradiction matrix for the design of quick positioning.

Avoid Deterioration Parameters Want to Improve Parameters	01. Weight of Moving Objects	31. Object-Generated Harmful Factors	36. Device Complexity
12. Shape	08, 10 29, 40	35, 01	16, 29 01, 28
27. Reliability	03, 08 10, 40	35, 02 40, 26	13, 35 01
33. Ease of operation	25, 02 13, 15		32, 26 12, 17

Based on the statistical results in Table 4, the three most frequently occurring inventive principles—01. (segmentation), 35. (parameter changes), and 40. (composite materials)—were selected as the basis for the design. These principles provide innovative solutions to enhance the alignment mechanism's functionality and environmental sustainability. The detailed explanation is as follows:

Table 4. The inventive principles for the design of quick positioning.

The Inventive Principles	Count
01. Segmentation	3
35. Parameter changes	3
40. Composite materials	3
02. Taking out	2
08. Counterweight	2
10. Preliminary action	2
13. The other way around	2
26. Copying	2
29. Fluid dynamics	2
03. Local quality	1
12. Equipotentiality	1
15. Dynamics	1
16. Partial or excessive action	1
17. Another dimension	1
25. Self-service	1
28. Mechanics substitution	1
32. Color changes	1

(1) Segmentation (No. 01): Dividing the alignment mechanism into simpler, more manageable parts to facilitate disassembly and disposal, enabling easier handling of each component after use;

(2) Parameter Changes (No. 35): Transforming the alignment mechanism into biodegradable materials, ensuring that the mechanism decomposes naturally after use, thus reducing environmental impact;

(3) Composite Materials (No. 40): Utilizing a combination of biodegradable and recyclable materials for the alignment mechanism to enhance its decomposability and environmental sustainability, making post-use disposal easier and more eco-friendly.

3.1.2. Ergonomic for Positioning

This study applied ergonomic principles to the quick alignment design of the food container and its lid, ensuring convenience and usability. Anthropometric data related to the hand, including hand size, finger dexterity, and grip strength, were analyzed to develop a design accommodating specific user groups. Target users included adult males and females aged 20–60 years, with hand dimensions derived from multiple studies. For instance, average hand lengths of 183.9 mm for males and 169.7 mm for females, as well as widths of 87.5 mm and 76.3 mm, respectively, were considered. Additionally, grip strength and dexterity were referenced, noting a strong positive correlation between hand length and grip strength (correlation coefficient >0.83) and variations in finger dexterity by age and gender [48–50].

The ergonomic positioning mechanism was designed to suit diverse users, enabling easy and precise alignment of the container and lid while minimizing operational fatigue and errors. Specific design features, such as finger grooves and optimized grip areas, were incorporated based on average and extreme anthropometric data for inclusivity. Multiple product sizes were considered to accommodate variations in user hand dimensions and preferences. Furthermore, habitual hand movements and wrist thickness were factored into the design of the controller, improving its usability, precision, and safety during operation.

3.1.3. Inherently Safe Positioning Design

To achieve a quick alignment design for the food container and lid, this study employed principles of simplification, mistake-proofing, and prevention of cascading failures. A sloped flange mechanism was designed to guide the alignment process, similar to the unidirectional connection found in mobile phone chips. Specifically, the flange features an angled slope that allows the container and lid to engage only in the correct orientation, preventing assembly errors. This mechanism is further inspired by the corner chamfer of square chips, which provides a clear physical cue to ensure proper alignment. The sloped flange not only guides the lid into the correct position but also eliminates the possibility of incorrect assembly. Additionally, a three-point positioning system works in tandem with the sloped flange to secure the container and lid, even if some locking points are not fully engaged. This design ensures stability during use, prevents content spillage, and enhances both safety and reliability.

3.1.4. Universal Design Principles for Positioning

The study improved the container's quick alignment system based on universal design principles, focusing on intuitive use, appropriate dimensions, and low-effort operation. The container was designed in various shapes—cylindrical, square, and rectangular—with single, double, or triple-point positioning mechanisms to facilitate easy handling. Specific positioning points were added to each shape, such as the central alignment design for cylindrical containers, ensuring a quick and secure connection with the lid. To reduce user effort, an L-shaped double-sloped flange mechanism was used, allowing users to lock the container with a light press and open it with a simple push, making the process efficient and user-friendly.

3.2. Easy Opening and Closing Design

3.2.1. TRIZ Method for Opening and Closing

This study applied the TRIZ contradiction matrix to design a food container with an easy opening and closing design. The identified improvement parameters were 10. (force), 14. (strength), and 33. (ease of use), while the parameters to avoid deterioration were 01. (weight of moving object), 31. (harmful side effects), and 36. (device complexity). The results of the contradiction matrix, including the corresponding inventive principles, are summarized in Table 5.

Table 5. Technical contradiction matrix for the design of easy opening and closing.

Avoid Deterioration Parameters Want to Improve Parameters	01. Weight of Moving Objects	31. Object-Generated Harmful Factors	36. Device Complexity
10. Force	08, 01 37, 18	13, 03 36, 24	26, 35 10, 18
14. Strength	01, 08 40, 15	15, 35 22, 02	02, 13 15, 18
33. Ease of operation	25, 02 13, 15		32, 26 12, 17

Based on the statistical analysis in Table 6, the three most frequently occurring inventive principles—15. (dynamics), 02. (taking out), and 13. (the other way around)—were selected as the foundation for the design. These principles provide innovative solutions to enhance the easy opening and closing design. The detailed explanation is as follows:

(1) Dynamics (No. 15): Incorporating dynamic components, such as spring-loaded or press-and-release mechanisms. This allows users to easily open the container while ensuring secure closure and simple joining through dynamic movement.

(2) Taking Out (No. 02): Designing the container with a pull-tab or specific release point for easy separation of parts. This approach minimizes unnecessary joints, making the container simple to open while maintaining its functionality and ease of use.

(3) The Other Way Around (No. 13): Implementing a reverse-action mechanism where users open the container in an unconventional manner. This design enhances safety and ensures that the container remains securely closed when not in use.

Table 6. The inventive principles for the design of easy opening and closing.

The Inventive Principles	Count
15. Dynamics	4
02. Taking out	3
13. The other way around	3
18. Mechanical vibration	3
01. Segmentation	2
08. Counterweight	2
26. Copying	2
35. Parameter changes	2
03. Local quality	1
10. Preliminary action	1
12. Equipotentiality	1
17. Another dimension	1
22. Blessing in disguise	1
24. Mediator	1
25. Self-service	1
32. Color changes	1
36. Phase transitions	1
37. Thermal expansion	1
40. Composite materials	1

3.2.2. Ergonomic Method for Opening and Closing

This study applied ergonomic principles to the design of a food container's easy-to-join and open mechanism, focusing on anthropometrics, human–machine interaction, and controller design. Anthropometric considerations such as hand size and finger dexterity were used to ensure that the container's dimensions were appropriate and that the force required to operate it was neither too great nor too small. The design aligns with natural hand and arm movements for enhanced comfort and convenience. A user-friendly human–machine interface with visual cues reduces the risk of operational errors and improves user experience. Controller design principles were also applied to provide tactile and visual feedback, ensuring ease of use, safety, and operational stability.

3.2.3. Inherently Safe Opening and Closing Design

To achieve a safe and easy-to-use joining and opening mechanism, this study adopted inherently safe design strategies, including simplification, mistake-proofing, and the prevention of cascading failures. The mechanism was designed to be intuitive and user-friendly by implementing a simplified L-shaped dual-flange system. This system consists of two interlocking flanges: one positioned horizontally along the rim of the container and the other extending vertically from the lid, forming an "L" shape when viewed in cross-section. These flanges guide the user during assembly, ensuring a smooth and straightforward alignment. To further enhance usability, mistake-proofing was achieved by incorporating uniquely shaped grooves and flanges with precisely matched dimensions. These features ensure that the container can only be connected or opened when aligned in the correct orientation, preventing misalignment or improper usage. Additionally, the design reduces the likelihood of accidental detachment by providing a secure fit that only releases when the specific unlocking motion is applied. The use of sloped flange connections enhanced this effect. To prevent cascading failures, multiple independent positioning points were incorporated, ensuring that the container remains securely connected even if one point fails, maintaining stability through a multi-point locking system.

3.2.4. Universal Design Principles for Opening and Closing

In the universal design of the easy-to-join and open mechanism, the study emphasized intuitive use, appropriate sizing, and effortless operation. The container design incorporated user-friendly shapes such as easy-grip handles and raised surfaces, with clear markings or icons at operation points to enable intuitive use. The dimensions were tailored to fit most hand sizes, providing sufficient space for comfortable operation. Ergonomic grooves or ridges were designed, and mechanisms that require minimal force to press or pull were employed, reducing the effort needed to open or close the container and ensuring convenience and accessibility for a wide range of users.

3.3. Applying TRIZ Methods to the Design of Fully Biodegradable Functions

This study applied the TRIZ contradiction matrix to design a fully biodegradable food container. The identified improvement parameters were 13. (stability of the object), 31. (harmful side effects), and 35. (adaptability), while the parameters to avoid deterioration were 02. (weight of stationary object), 12. (shape), and 27. (reliability). The results of the contradiction matrix, including the corresponding inventive principles, are summarized in Table 7.

Table 7. Technical contradiction matrix for the design of fully biodegradable functions.

Avoid Deterioration Parameters **Want to Improve Parameters**	**02. Weight of Stationary Objects**	**12. Shape**	**27. Reliability**
13. Stability of object's composition	26, 39 01, 40	22, 01 18, 04	
31. Object-generated harmful factors	35, 22 01, 39	35, 01	24, 02 40, 39
35. Adaptability or versatility	19, 15 29, 16	15, 37 01, 08	35, 13 08, 24

Based on the statistical analysis in Table 8, the three most frequently occurring inventive principles—01. (segmentation), 35. (parameter changes), and 39. (inert environment)—were selected as the foundation for the design. These principles provide innovative solutions to develop a fully biodegradable food container. The detailed explanation is as follows:

Table 8. The inventive principles for the design of fully biodegradable functions.

The Inventive Principles	**Count**
01. Segmentation	5
35. Parameter Changes	3
39. Inert Environment	3
08. Counterweight	2
15. Dynamics	2
22. Turning Harmful into Beneficial	2
24. Intermediary	2
40. Composite Materials	2
02. Taking Out	1
04. Asymmetry	1
13. The Other Way Around	1
16. Excessive Action	1
18. Mechanical Vibration	1
19. Periodicity	1
26. Copying	1
29. Pneumatics or Hydraulics	1
37. Thermal Expansion	1

(1) Segmentation (No. 01): Dividing the components into smaller, naturally degradable units to facilitate the decomposition process. The container is made of biodegradable materials and designed to break down easily in the environment, accelerating degradation.

(2) Parameter Changes (No. 35): Adjusting parameters to optimize the container's design for various environmental conditions. For example, modifying material properties such as permeability or biodegradability to ensure effective breakdown.

(3) Inert Environment (No. 39): Creating favorable conditions for degradation even in less-than-ideal environments. The container can include catalysts or specific features that promote decomposition.

3.4. Selection and Testing of Biodegradable Materials

This study first analyzed commonly available biodegradable materials alongside other material types to understand their distinct characteristics and select the most suitable option. Comparative analysis revealed that biodegradable materials offer significant advantages over traditional plastics, as shown in Table 9. These materials excel in environmental performance, acid resistance, antimicrobial properties, and complete decomposition into carbon dioxide and water.

Table 9. Comparison of food container materials.

	Fully Biodegradable Materials	Partially Biodegradable Materials	Foam Material
Heat resistance	Excellent	Fair	Poor
Water resistance	Excellent	Fair	Good
Acid resistance	Excellent	Poor	Poor
Antimicrobial properties	Excellent	Poor	Fair
Environmental friendliness	Excellent	Fair	Poor
Cost	High	Medium	Low

Fully biodegradable materials refer to those that can completely break down into natural substances such as carbon dioxide, water, and biomass under standard composting conditions. Examples include polylactic acid (PLA) and starch-based polymers, which were used in this study for their ability to provide structural integrity and complete decomposition. Partially biodegradable materials, such as polycaprolactone (PCL) blends, degrade only to a certain extent and were excluded from the final design due to potential environmental residues. Foam materials, commonly classified as expanded polystyrene (EPS), are typically non-biodegradable, but biodegradable foam alternatives like cornstarch-based foam were evaluated for their lightweight and cushioning properties.

In this study, the selected fully biodegradable materials were configured based on their specific purposes. PLA was used for its strength and thermal resistance, making it ideal for the container's structural components, while starch-based polymers were chosen for their flexibility and compatibility with food-grade applications. The final combination of materials was tested under specific conditions, including microwave exposure, acid resistance, and cold resistance, to validate performance and ensure suitability for practical use. Microwave testing involved heating the sample in a microwave oven at 750W for 2 min. Visual inspection showed no significant changes in appearance, indicating that the material retains its physical properties under microwave conditions, confirming its safety and suitability for microwave use.

Cold resistance testing was conducted by SGS Taiwan Limited's Hardline Laboratory using the KSON/THS-G4T-150 equipment (Taichung City, Taiwan). The sample was exposed to a low-temperature environment for 1 h, followed by temperature equilibration at room temperature. Visual inspection revealed no damage, confirming that the material maintains structural integrity at extreme temperatures as low as -50 °C, demonstrating its excellent cold resistance and competitive edge for applications like frozen storage and low-temperature transport.

Acid resistance testing was also performed by SGS Taiwan Limited's Hardline Laboratory to ensure accuracy and reliability. The sample was fully immersed in a citric acid solution with a pH of 2.5 for 24 h. Post-immersion visual inspection showed no damage or changes in appearance, indicating that the material possesses good acid resistance, maintaining its physical properties and appearance in acidic environments.

4. Results

4.1. Design of the Product Structure

To address the environmental challenges posed by conventional plastic food containers—such as their persistence in the environment as long-lasting waste, slow degradation, and failure to comply with government restrictions on plastic use—this study developed a fully biodegradable food container. The design integrated features such as rapid positioning, ease of use, and eco-friendly materials to enhance both user convenience and environmental sustainability.

The container body was made from a combination of biodegradable materials that provide excellent strength, durability, and complete biodegradability. These materials support sustainability goals while ensuring the container withstands everyday stresses such as stacking, carrying, and washing. The selected materials offer a balance of rigidity and flexibility to ensure structural integrity and a secure fit between components.

The internal structure was ergonomically optimized to address specific user needs, focusing on reducing physical strain during handling and improving usability. For example, the container's design minimizes the force required to open or close it, making it suitable for elderly users or those with limited hand strength. The target group includes diverse demographics, such as families, office workers, and individuals in transit, ensuring versatility and practicality for daily use.

A key innovation is the rapid positioning mechanism, a groove-and-flange system at the junction of the container and lid, enabling users to align and secure the lid quickly and accurately. This mechanism reduces operational complexity and enhances user confidence. Furthermore, the design incorporates an inclusive spring-loaded or push-button opening mechanism, ensuring ease of use for people of all ages and abilities. For instance, children and individuals with arthritis can open the container effortlessly, reflecting the principles of Universal Design.

To meet a range of demographic needs, the container is available in various shapes and sizes, accommodating different food portions and preferences. For example, small containers are ideal for snacks or meal prep, while larger versions suit family-sized meals. The tight-fitting lid prevents leakage, preserves food freshness, and minimizes waste, contributing to the product's eco-friendliness.

By combining user-focused ergonomic design, eco-friendly material selection, and innovative features, this study presents a fully biodegradable container that aligns with global sustainability goals and enhances everyday convenience.

4.2. Quick Positioning Design

The container's joint design employed inclined surfaces and downward-curved panels to ensure a secure and tight fit between the lid and the container body, effectively preventing the leakage of food and liquids. This design not only improves the sealing capability of the container but also ensures safety and hygiene during use, supporting sustainability by minimizing food waste and reducing the need for additional packaging or containers. The robust sealing properties contribute to extending the freshness of stored food, thereby aligning with sustainability goals related to waste reduction and resource efficiency.

To accommodate various container forms and optimize storage efficiency in restaurants, this study developed designs with different shapes and positioning structures tailored to specific usage scenarios. These positioning designs ensure precise alignment and secure engagement between the lid and the container body, mitigating misalignment issues that could compromise the container's functionality. Furthermore, the improved stacking capability of these containers enhances space efficiency, contributing to reduced storage and transportation costs, which in turn lowers the environmental footprint associated with logistics.

Table 10 provides a visual and descriptive comparison of various positioning design types used in circular, square, and rectangular food containers. Each row includes an image placeholder and a corresponding explanation, highlighting the unique features, applications, and advantages of single-point, two-point, and three-point positioning designs. This table serves as a guide to understanding how these designs enhance usability, stability, and sealing effectiveness for different food storage needs.

Table 10. Comparison of various positioning designs for food containers.

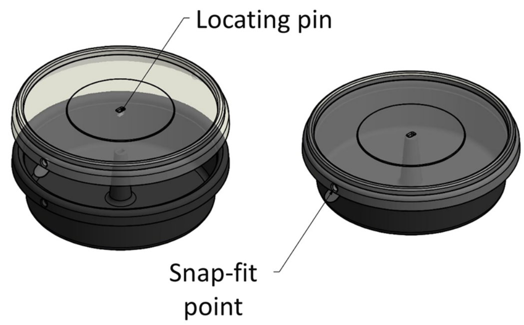
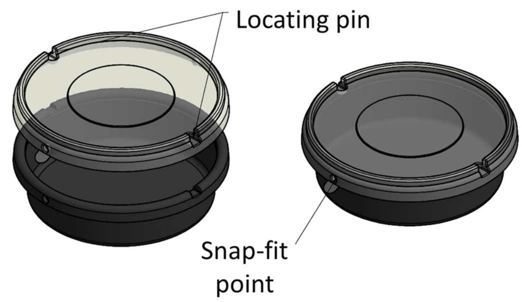
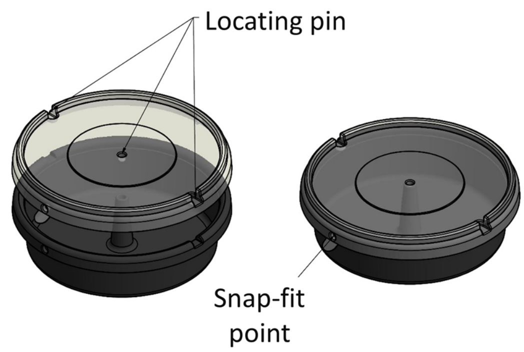
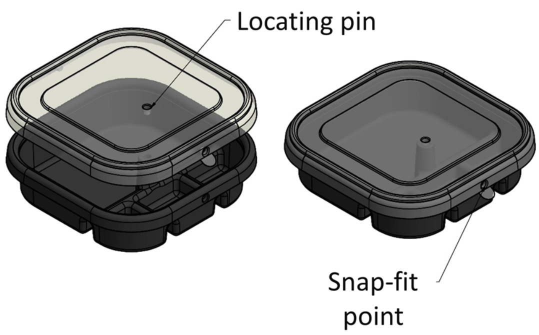
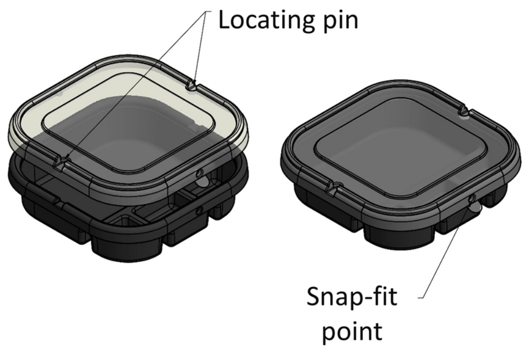
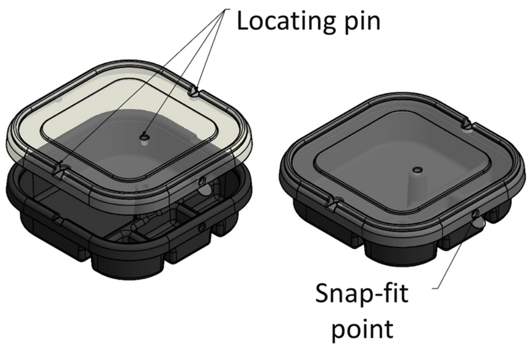
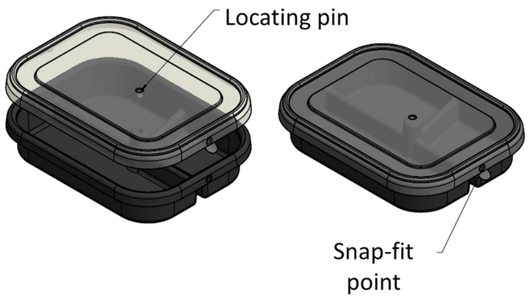
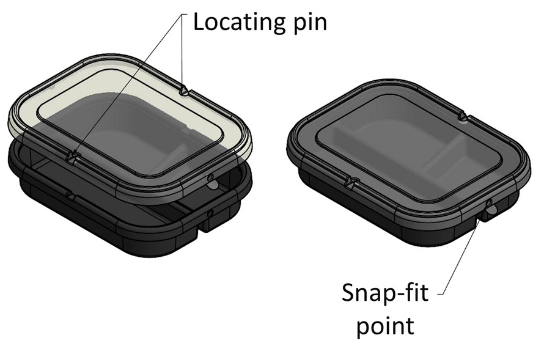
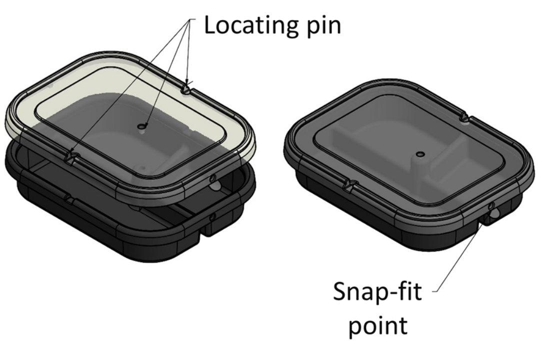
Schematic Diagram	Description
	**Circular Container—Single-Point Positioning Design:** Features a central alignment point on both lid and body for simple and rapid assembly. Ideal for small, low-stability food items.
	**Circular Container—Two-Point Positioning Design:** Includes two alignment points on opposite sides of the lid and body, enhancing sealing effectiveness and providing stability for moderately fluid foods.
	**Circular Container—Three-Point Positioning Design:** Distributes three alignment points evenly around the lid and body, ensuring multi-point support and maximum stability for fluid food items, preventing spillage.
	**Square Container—Single-Point Positioning Design:** Features a positioning point at one corner of the lid and base, enabling quick assembly and ease of use. Best for small food portions.

Table 10. *Cont.*

Schematic Diagram	Description
	**Square Container—Two-Point Positioning Design:** Positioning points at diagonal corners enhance alignment accuracy and sealing. Suitable for foods requiring secure handling.
	**Square Container—Three-Point Positioning Design:** Aligns points at three corners, ensuring even pressure distribution and maximum stability. Ideal for mixed-consistency food combinations.
	**Rectangular Container—Single-Point Positioning Design:** Features a central alignment point for easy assembly, suited for smaller, less-stable food portions.
	**Rectangular Container—Two-Point Positioning Design:** Places alignment points along the longer sides, improving sealing effectiveness and stability for long food items.
	**Rectangular Container—Three-Point Positioning Design:** Distributes alignment points around the perimeter for even support and maximum stability, perfect for diverse meals and foods with varying consistencies.

4.3. Easy Opening and Closing Design

The design of various container shapes incorporates mechanisms to ensure ease of engagement and opening, with specific methods for alignment and operation that prioritize user convenience and efficiency. For circular containers, users can engage the lid by gently pressing on the edge with their thumb and index finger, then lifting it upward along the edge. To maintain proper sealing after placing food inside, it is crucial to ensure that the food does not exceed the container's edge, as this could compromise the seal. When closing the lid, it should be aligned with the container's edge and pressed down evenly until a slight click is heard, indicating that the lid is securely closed.

Table 11 presents a comparative analysis of alignment designs for circular, square, and rectangular containers, emphasizing the functional characteristics and advantages of single-point, two-point, and three-point configurations. The descriptions focus on key aspects such as assembly simplicity, sealing performance, and structural stability, providing a comprehensive overview of how these designs meet various user and environmental requirements. The analysis underscores their contributions to enhanced usability, effective food preservation, and sustainability.

Table 11. Easy opening and closing designs for food containers.

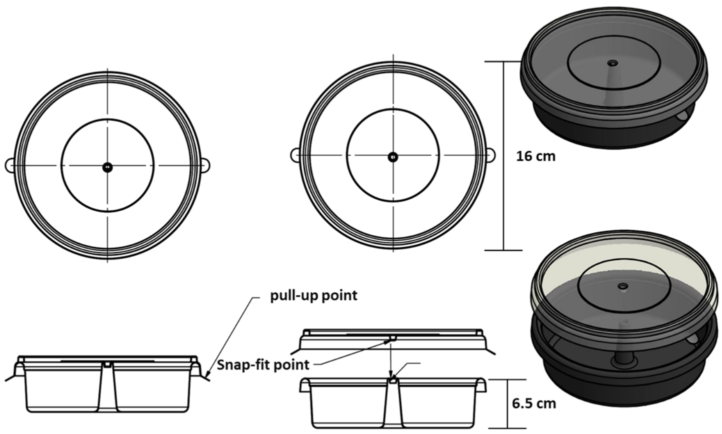
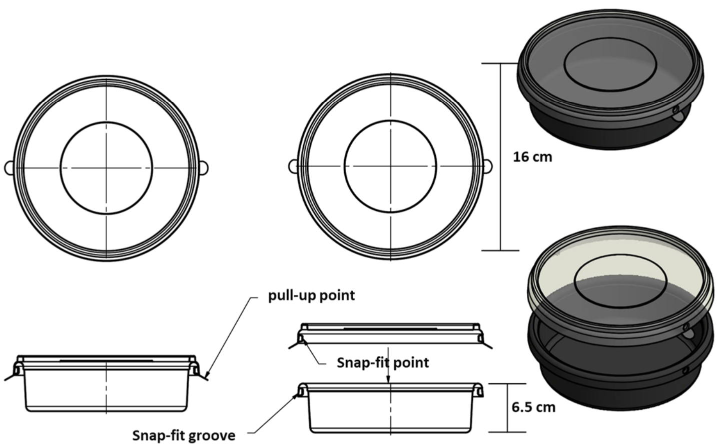
Schematic Diagram	Description
 	**Circular Container—Single-Point Design:** Central alignment point on both lid and base ensures easy and quick assembly. Suitable for small portions, reducing complexity and spillage risk.
 	**Circular Container—Two-Point Design:** Alignment points on opposite sides of the lid and base improve sealing effectiveness and provide better stability for moderately fluid foods.

Table 11. *Cont.*

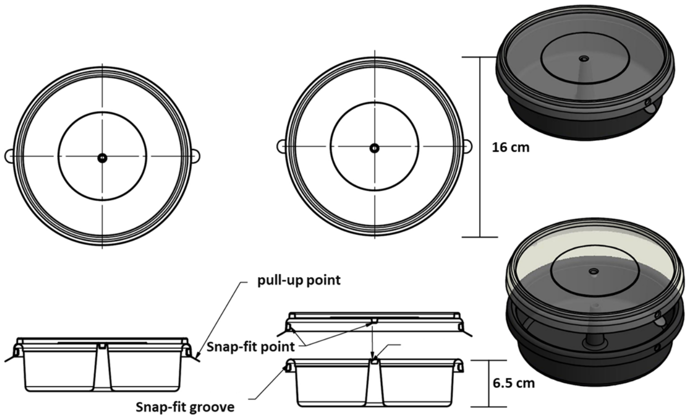
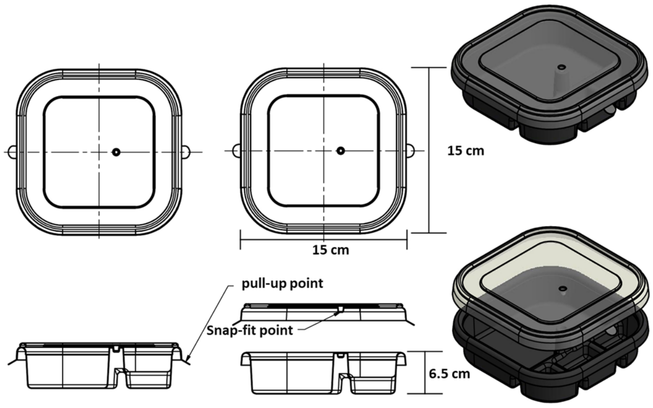
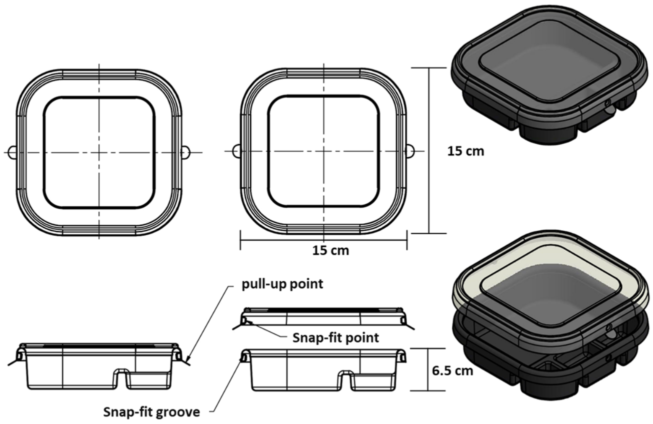
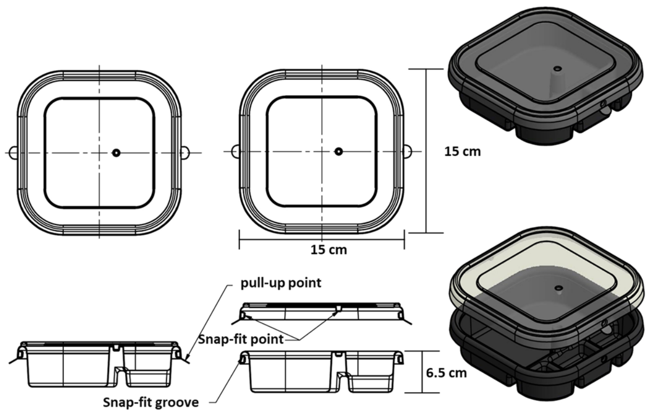
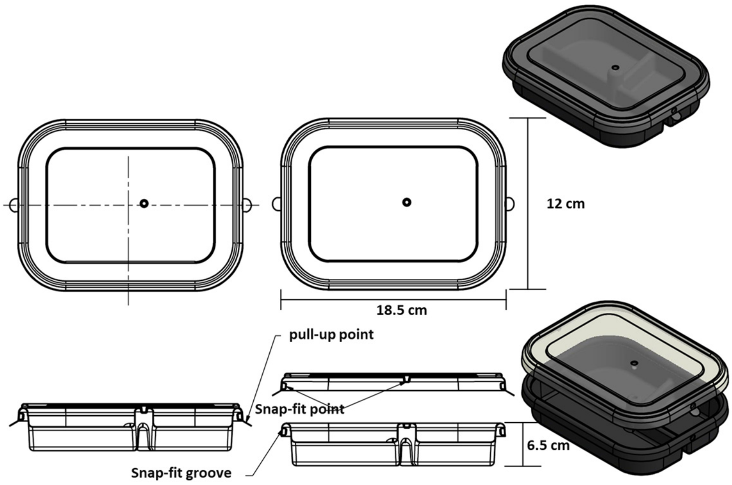
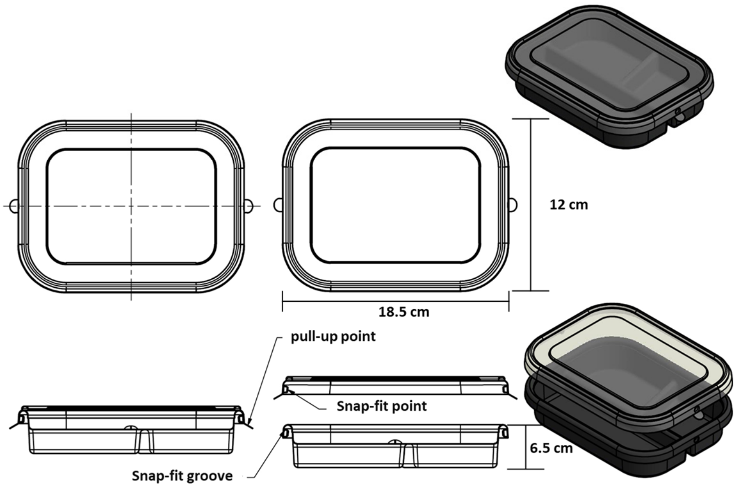
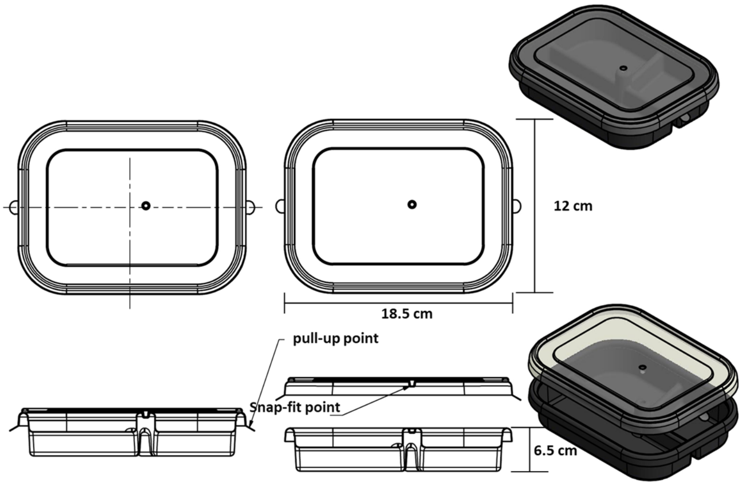
Schematic Diagram	Description
	**Circular Container—Three-Point Design:** Three alignment points evenly distributed ensure multi-point support and even pressure distribution, ideal for highly fluid foods to prevent spillage.
	**Square Container—Single-Point Design:** An alignment point at one corner of the lid and base allows for quick and straightforward assembly, ideal for smaller food portions.
	**Square Container—Two-Point Design:** Positioning points at diagonal corners increase alignment accuracy and sealing, offering greater stability for secure food handling.
	**Square Container—Three-Point Design:** Three alignment points at the corners ensure uniform pressure distribution and maximum stability, suitable for diverse food combinations.

Table 11. *Cont.*

Schematic Diagram	Description
	**Rectangular Container—Single-Point Design:** Central alignment point simplifies assembly, ideal for small, low-stability food portions. Reduces the risk of leakage.
	**Rectangular Container—Two-Point Design:** Alignment points on the longer sides improve sealing effectiveness, providing greater stability for long or larger food items.
	**Rectangular Container—Three-Point Design:** Three alignment points around the perimeter offer maximum stability and even pressure distribution, ideal for mixed-consistency foods and larger meals.

4.4. Fully Biodegradable Functions

The food container and lid incorporated advanced biodegradable technology developed by our research team. This technology ensures that both the container and lid decompose into water and fine particles within one month, fully integrating into standard soil while maintaining soil functionality. The use of fully biodegradable materials ensures that the container does not contribute to long-term environmental pollution, effectively addressing the issue of traditional plastic containers' slow degradation and reducing the overall impact of plastic waste on the environment.

Additionally, the container features a modular design that facilitates easy disassembly and decomposition. Each component is designed to degrade rapidly, accelerating the overall biodegradation process. The modular design also increases flexibility, allowing users to adjust the container's size and shape according to their needs, enhancing its practicality and convenience. Furthermore, this modular approach supports standardization in production, improving manufacturing efficiency and reducing waste. The container includes ventilation holes to promote airflow during the degradation process, which accelerates biodegradation and helps prevent food spoilage by allowing excess moisture and air to circulate, thereby maintaining food freshness and quality.

The design balances functionality with environmental sustainability, achieving a dual benefit. The incorporation of a thin-wall design reduces material usage while maintaining the container's strength, promoting faster degradation. This environmentally friendly approach is also economically advantageous, as it lowers material costs and makes the container lighter, enhancing user portability. This design philosophy aligns with sustainable development goals and improves the product's market competitiveness. By ensuring complete degradation post-use, the container minimizes environmental pollution and contributes to sustainability objectives. These innovative features reflect the research team's dedication to environmental protection and demonstrate advancements in material science and industrial design. The container represents a successful integration of environmental friendliness and practicality, offering a more sustainable solution for food containers in the market.

5. Discussion

In this study, we successfully developed a fully biodegradable food container that integrates advanced TRIZ methodologies, ergonomic principles, inherent safety designs, and universal design approaches. The outcome presents a solution that is both practical for users and environmentally sustainable. By focusing on material selection, modular design, and easy-to-use mechanisms, this container addresses critical issues in conventional food packaging, such as plastic waste, poor usability, and high environmental impact.

Advancements in 4D printing technology for food transportation and storage highlight innovative strategies that could inform future iterations of sustainable packaging. For example, the ability to design flat-packed, shape-transforming containers through 4D printing offers opportunities to optimize transportation efficiency and reduce storage space requirements [51]. By drawing inspiration from these principles, our modular design not only enhances functionality but also aligns with the broader goal of integrating automated production and customization in packaging solutions. This convergence of sustainability and adaptability ensures the container meets both user demands and environmental objectives.

The core of the design lies in its biodegradability, which ensures that the container decomposes into water and fine particles within a short period. Unlike traditional materials such as polylactic acid (PLA), which, while labeled biodegradable, often require specific industrial composting conditions—such as high temperatures and controlled microbial environments—for effective decomposition, the material used in this design degrades naturally under typical environmental conditions [52,53]. This eliminates the dependence on specialized infrastructure, addressing a significant limitation of PLA-based products.

By minimizing the long-term environmental pollution caused by traditional plastics and overcoming the challenges associated with PLA, this design contributes more effectively to global sustainability efforts. The modular approach further enhances product flexibility and supports user adaptability while promoting more efficient manufacturing processes through standardization. Additionally, features such as ventilation holes and a thin-wall design align with sustainability principles by reducing material usage and accelerating the degradation process, making the container an ideal solution for both ecological and practical needs.

The ergonomically optimized design contributes to the ease of use for a diverse range of users, ensuring functionality without compromising comfort or safety [28,54,55]. Drawing on insights from ergonomic design in assistive devices, such as self-help lifting pads tailored for elderly users, the importance of iterative prototyping and user-centered adjustments becomes evident [56]. Similarly, our design process incorporated feedback loops to address diverse user needs, emphasizing material selection and functional adaptability to ensure inclusivity and usability. The integration of inherent safety principles strengthens the product's reliability, preventing failures that could lead to food spillage or contamination. Moreover, the universal design approach emphasizes inclusivity, ensuring that users of all ages and abilities can operate the container with minimal effort.

In terms of environmental impact, the use of fully biodegradable materials and the incorporation of sustainable design elements, such as material efficiency and modularity, provide significant environmental benefits. This design not only reduces the carbon footprint associated with plastic waste but also promotes a circular economy by enabling the complete degradation of materials after use. The container's lifecycle—from production to disposal—illustrates a well-balanced approach between user convenience and environmental sustainability.

The results of this research demonstrate that integrating TRIZ-based innovation systems with sustainability-driven design principles can lead to the development of products that meet both consumer demands and environmental objectives. The food container represents a successful case of combining cutting-edge material science with practical, user-friendly design, offering a blueprint for future innovations in sustainable packaging.

This study acknowledges several limitations that may impact its findings. The performance of the proposed container was tested under specific laboratory conditions, which may not fully reflect real-world usage scenarios. And the production costs of bio-degradable materials remain higher than those of conventional plastics, potentially limiting scalability and commercial adoption. Additionally, regional differences in waste management infrastructure and recycling capabilities may affect the container's overall environmental impact, highlighting the need for localized assessments.

Future research should explore expanding the scope of biodegradable materials to include hybrid solutions that combine sustainability with enhanced functionality, such as antimicrobial properties or thermal resistance. Additionally, long-term field studies in diverse environmental settings are needed to evaluate the practical performance and degradation efficiency of the proposed containers under real-world conditions. Investigating cost-reduction strategies for biodegradable materials, including advancements in manufacturing processes, could further support commercial scalability. Finally, interdisciplinary collaboration involving materials science, industrial design, and waste management is crucial to developing comprehensive solutions that address both environmental and economic challenges.

6. Conclusions

This research has developed an innovative food container that integrates rapid alignment, ease of assembly and opening, and full biodegradability. Through a comprehensive exploration of product structure, material selection, and pioneering design principles, this container achieves not only superior usability and ergonomics but also exemplifies a harmonious balance between environmental sustainability and practical utility. Its unique alignment system ensures precise fitting between the lid and container body, while the sloped and curved design facilitates smoother operation and effectively prevents spillage.

The container's biodegradable material ensures it decomposes into environmentally benign components within a short period, addressing the critical issue of plastic waste and contributing to global sustainability goals. Additionally, the container's modular design enhances production efficiency and allows for greater flexibility in its use, adapting to various consumer needs while minimizing resource consumption.

This study highlights significant advancements in both the practicality and environmental impact of food containers, reinforcing the importance of sustainable practices in the design and development of eco-friendly utensils. The findings contribute valuable insights into the application of biodegradable materials and green design, underscoring the role of innovation in promoting long-term environmental stewardship.

7. Patents

The research results were awarded a utility model patent by the Intellectual Property Office, Ministry of Economic Affairs, Republic of China (Patent No. M644187).

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Conflicts of Interest: Author Hsi-Huang Hsieh was employed by the company Yaw Shuenn Industrial Co., Ltd. Author Jing-Ran Xu was employed by the company Sheng Jen Industrial Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflicts of interest.

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