https://doi.org/10.53964/jmim.2024012

https://www.innovationforever.com

Journal of
Modern Industry and Manufacturing

ISSN 2788-8096 (Online)

Open Access

Review

Redefining Packaging Solutions: The Advantages of Split-layer Packaging for Waste Reduction and Climate Action

Yenni Ciawi[1*], **Silvia Gabrina Tonyes**[1], **Ni Made Utami Dwipayanti**[2]

[1]Doctoral Program in Engineering Sciences, Engineering Faculty, Udayana University, Indonesia

[2]Department of Public Health, Faculty of Medicine, Udayana University, Indonesia

[*]**Correspondence to: Yenni Ciawi, PhD,** Doctoral Program in Engineering Sciences, Faculty of Engineering, Udayana University, Jl.PB Sudirman, Denpasar, Bali 80234, Indonesia; Email: yenniciawi@unud.ac.id

Received: August 3, 2024 **Revised:** September 10, 2024 **Accepted:** October 8, 2024 **Published:** November 26, 2024

Abstract
The widespread use of multilayer packaging in industries such as food, beverages, pharmaceuticals, and cosmetics is driven by its ability to provide superior protection against environmental factors. However, the complex composition of multilayer packaging, involving bonded layers of different materials, presents substantial challenges for recycling, leading to low recycling rates and significant landfill accumulation. This study explores the potential of double packaging, which employs easily separable layers, as a solution to enhance recycling efficiency and mitigate environmental impacts. Primary recycling methods, including mechanical and chemical processes, are examined alongside advanced techniques like solvent-based and enzymatic recycling. Design considerations for double packaging are analyzed, emphasizing the use of minimal materials and adhesives, strategic sealing, and clear labeling to facilitate recyclability. Case studies from the food, beverage, and cosmetics sectors highlight the practical benefits of double packaging, demonstrating improvements in recycling rates, cost-effectiveness, and consumer compliance. The findings suggest that double packaging significantly simplifies the recycling process, reduces dependency on landfills, and lowers greenhouse gas emissions by decreasing the need for virgin materials. Effective implementation requires industry collaboration, regulatory support, economic incentives, investment in innovative recycling technologies, and robust consumer education programs. Double packaging emerges as a viable strategy for advancing sustainable packaging solutions and promoting a circular economy.

Keywords: multilayer packaging, recycling challenges, split-layer packaging, environmental impact, sustainable packaging

Citation: Ciawi Y, Tonyes SG, Dwipayanti NMU. Redefining Packaging Solutions: The of Split-layer Packaging for Waste Reduction and Climate Action. *J Mod Ind Manuf*, 2024; 3: 12. DOI: 10.53964/jmim.2024012.

1 INTRODUCTION

The demand for effective packaging solutions has driven the widespread adoption of multilayer packaging across various sectors, including food, beverage, pharmaceuticals, and cosmetics. These materials are designed to protect products from environmental factors such as moisture, oxygen, and light, thereby extending shelf life and maintaining product integrity[1]. However, the intricate structure of multilayer packaging, typically composed of different materials bonded together, poses significant challenges to recycling efforts[2]. Companies and researchers pay much attention to the back-end recycling of plastic packaging wastes, but the front-end design for recycling plastic packaging is often ignored[3]. The inability to efficiently separate these bonded layers results in low recycling rates, with approximately 15% of municipal solid waste consisting of multilayer packaging[4]. This reliance on landfills for disposal exacerbates environmental pollution and contributes to greenhouse gas emissions, particularly methane, which is released during the decomposition of organic materials in landfills[5].

In contrast, split-layer packaging presents a promising alternative to traditional multilayer packaging by simplifying recycling, reducing costs, and lowering emissions. This innovative approach allows for the use of easily separable layers, which can facilitate efficient recycling processes and minimize environmental impact. However, despite its potential benefits, challenges remain in scaling up split-layer packaging across different industries. This paper aims to explore the concept of split-layer packaging, its benefits, case studies demonstrating its effectiveness, and the alignment of this packaging approach with global sustainability goals and regulatory frameworks.

1.1 Environmental Impact of Multilayer Packaging Waste

The environmental impact of multilayer packaging waste is profound. When disposed of in landfills, these materials can take hundreds of years to decompose, releasing methane, a potent greenhouse gas that contributes significantly to climate change. The persistence of non-biodegradable materials in the environment leads to long-term pollution, with microplastics emerging as a major concern[6,7].

1.2 Microplastics and Their Risks

Microplastics are tiny plastic fragments that result from the degradation of larger plastic items. They can contaminate soil and water, posing risks to wildlife and human health. Studies have shown that microplastics can enter the food chain, affecting various species and potentially causing harm to human health through bioaccumulation. Furthermore, the incineration of plastic waste can release toxic substances, such as dioxins and furans, which have detrimental effects on both environmental and human health[8].

2 METHODS

This review employs a systematic approach to gather and analyze relevant literature on split-layer packaging and its role in improving recycling efficiency. Literature was sourced from three major databases: Google Scholar, PubMed, and ResearchGate. Search terms such as "split-layer packaging," "multilayer packaging recycling," and "sustainable packaging" were used to identify articles focusing on the food, beverage, and cosmetics industries, with an emphasis on mechanical, chemical, solvent-based, and enzymatic recycling methods.

2.1 Inclusion and Exclusion Criteria

Only peer-reviewed papers, case studies, and publications from the last ten years were included in the analysis to ensure the relevance of the findings. Articles that focused on innovations in recycling technologies, design considerations, and sustainability in packaging were prioritized. Papers that were outdated, irrelevant, or focused on industries outside the scope of the review were excluded.

2.2 Data Extraction and Analysis

Key information on design considerations, recycling methods, and outcomes of split-layer packaging was extracted from the selected literature. Case studies showcasing improvements in recycling rates, cost-effectiveness, and consumer compliance were emphasized. Alongside the synthesis of trends, challenges, and opportunities from the literature, the paper also integrates the author's own insights, drawing from critical analysis to assess the potential of split-layer packaging in advancing sustainable packaging solutions.

3 RECYCLING CHALLENGES

Recycling multilayer packaging is particularly challenging due to the complexity of its material composition. The intricate structure of multilayer packaging, which often consists of various bonded materials, complicates the recycling process and results in low recycling rates[9]. Current recycling technologies frequently fall short in efficiently processing these materials, leading to increased landfill use and environmental pollution[10].

3.1 Mechanical Recycling

Mechanical recycling is the most common method for processing plastic waste. This method involves melting and reprocessing plastic materials to create new products. However, multilayer packaging often comprises different types of plastics that can have incompatible melting points and chemical properties[11]. This incompatibility makes it difficult to recycle these materials together without compromising the quality of the recycled product. For instance, when different plastics are melted together, they may not bond properly, leading to a lower quality material that is less suitable for manufacturing new products. Additionally, the presence of additives, such as colorants and stabilizers, can further complicate the mechanical recycling process by affecting the melting behavior and properties of the recycled material[12,13].

3.2 Chemical Recycling

Chemical recycling, which breaks down plastics into their monomers or other chemical feedstocks, offers a potential solution to the challenges faced by mechanical recycling. This method can process a wider variety of plastic types, including those that are difficult to recycle mechanically. By converting plastics back into their basic building blocks, chemical recycling can produce high-quality raw materials that can be used to manufacture new plastics. However, chemical recycling technologies are still

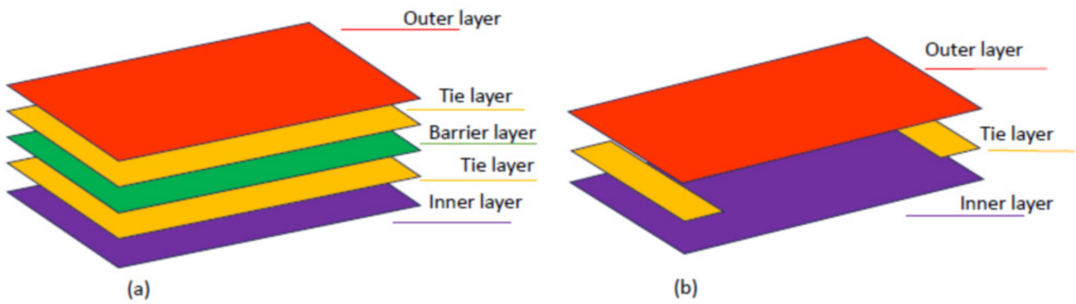

Figure 1. Structural Diagram of Multilayer Packaging[19](a) and Split Layer Packaging (b).

in their early stages of development. They can be energy-intensive and costly, which raises concerns about their overall sustainability and economic viability. Moreover, the presence of contaminants and additives in multilayer packaging materials can complicate the chemical recycling process, as these substances may interfere with the breakdown and purification of the recycled materials[11,13].

3.3 Advanced Recycling Technologies

In addition to mechanical and chemical recycling, there are emerging advanced recycling technologies that aim to enhance the recycling of multilayer packaging. For example, solvent-based recycling uses solvents to dissolve specific types of plastics, allowing for the separation of different materials. This method can effectively recover high-purity plastics from multilayer packaging[14]. Another innovative approach is enzymatic recycling, which employs enzymes to break down plastics into their monomers[15]. This method has shown promise for certain types of plastics and could potentially be applied to multilayer packaging in the future.

3.4 Challenges and Opportunities

Despite the potential of these recycling methods, several challenges remain. The economic feasibility of advanced recycling technologies is still being evaluated, and widespread adoption will require significant investment in infrastructure and technology[3,9,16]. Additionally, consumer awareness and participation in recycling programs are crucial for improving recycling rates. Education campaigns that inform consumers about the recyclability of multilayer packaging and the importance of proper disposal can help increase participation in recycling efforts[17,18].

4 SPLIT-LAYER PACKAGING: CONCEPT AND BENEFITS

Split-layer packaging is characterized by the use of two distinct layers that serve different functions and can either be fully detached or connected with minimal adhesive, such as a very thin tie layer. For example, an inner plastic wrap can offer moisture resistance, while an outer cardboard layer provides structural support (Figure 1), including applications like the bag-in-box concept. This innovative design enhances the recycling process by allowing each layer to be individually sorted and processed. The barrier layer, which protects against moisture and gases, can be placed as either the inner or outer layer based on specific packaging needs. Moreover, the tie layer traditionally used to bond these materials can be reduced or eliminated, making material separation during recycling even easier. This method exemplifies the principles of structures that are simple to assemble and disassemble[3].

4.1 Simplifying Recycling

One of the primary benefits of split-layer packaging is the simplification of the recycling process. By employing distinct and separable layers, split-layer packaging facilitates easier sorting and processing of materials. This can lead to higher recovery rates, as homogeneous materials are generally easier to recycle than composite ones. The separation of materials in split-layer packaging can be achieved through manual or automated sorting processes. Manual sorting involves workers separating the different layers by hand, while automated sorting employs advanced technologies such as optical sorting and near-infrared spectroscopy to identify and separate materials based on their properties. Both methods can significantly improve the efficiency and effectiveness of the recycling process[20].

4.2 Cost-Effectiveness

Split-layer packaging can also be cost-effective. By reducing the complexity of materials used[21], split-layer packaging can lower production costs. The use of easily separable layers can reduce the need for sophisticated recycling technologies, further lowering costs. The production of split-layer packaging can benefit from economies of scale; as the demand for sustainable packaging solutions increases, manufacturers can invest in more efficient production processes and technologies[21,22], reducing the cost of split-layer packaging materials.

Furthermore, the improved recyclability of split-layer packaging can create value through the recovery of high-quality recycled materials, which can be utilized in the production of new packaging[23].

4.3 Consumer Convenience

Split-layer packaging offers consumer convenience by providing clear instructions for disposal and recycling. This ensures that materials are properly directed to their respective recycling streams, improving overall recycling rates. Clear labeling and minimal adhesives are crucial in guiding consumers on how to dispose of each component properly[18]. Consumer education and awareness are essential for the success of split-layer packaging. Packaging labels should include straightforward instructions on how to separate and recycle the different layers. Public awareness campaigns and educational programs can also help consumers understand the benefits of split-layer packaging and encourage them to participate in recycling efforts[18,24].

4.4 Environmental Benefits of Split-layer Packaging

Split-layer packaging can help reduce greenhouse gas emissions by decreasing the need for virgin materials and reducing energy consumption. Recycling materials typically requires less energy than producing new ones, leading to lower carbon emissions. Additionally, by diverting waste from landfills, split-layer packaging reduces the release of methane and other greenhouse gases. The production of virgin plastic materials involves the extraction and processing of fossil fuels, which are associated with significant greenhouse gas emissions[25]. By increasing the recycling rate of packaging materials, split-layer packaging can reduce the demand for virgin plastics, leading to lower emissions from the production process. Furthermore, the use of renewable energy sources in the recycling process can further reduce the carbon footprint of packaging[26].

4.5 Decreasing Landfill Dependence

Split-layer packaging reduces landfill dependence by improving recycling rates. By making it easier to separate and process materials, split-layer packaging ensures that more materials are recycled and less waste ends up in landfills. This reduces the environmental impact of packaging waste and helps preserve landfill space. Landfill space is a finite resource, and many landfills are reaching their capacity[25]. By diverting waste from landfills through improved recycling practices, split-layer packaging can help alleviate the pressure on landfill sites and extend their lifespan. Additionally, reducing the amount of waste sent to landfills can decrease the environmental and health risks associated with landfill operations, such as groundwater contamination and air pollution[25].

5 DESIGN CONSIDERATIONS FOR SPLIT-LAYER PACKAGING

In designing split-layer packaging, several considerations are critical to ensure its effectiveness and sustainability.

5.1 Use of Minimal Materials

To further enhance the sustainability of split-layer packaging, it is essential to adopt a design philosophy centered around the use of minimal materials. This approach not only reduces the environmental footprint of the packaging but also contributes to cost savings and resource efficiency. By optimizing the amount of material used for both the inner and outer layers, manufacturers can achieve a balance between functionality and sustainability. For instance, thinner plastic films can be used for moisture resistance, while lightweight cardboard or paper can provide structural support. Additionally, reducing the volume of adhesives and other auxiliary materials ensures that each component can be easily separated and recycled. This minimalist approach aligns with the principles of eco-design, which emphasize the reduction of waste and the efficient use of resources throughout the product's lifecycle. By prioritizing minimal material use, split-layer packaging can significantly reduce the consumption of raw materials, lower transportation emissions due to lighter packaging, and enhance the overall recyclability of the packaging components. Table 1. presents the optimal dimensions for various geometric shapes used in packaging, calculated to ensure minimum material use while maximizing volume efficiency. It highlights how material can be conserved by optimizing the surface area to volume ratio, contributing to more sustainable and cost-effective packaging solutions.

Explanation of Additional Shapes:

(1) Ellipsoid:

The ellipsoid has three semi-principal axes a, b, and c. The volume equation is given by $V = \frac{4}{3}\pi abc$.

The surface area of an ellipsoid is generally approximated, as there's no simple exact formula, but it's roughly $A \approx \pi ((ab+ac+bc)^3)^2/^3$

Minimizing the surface area for a given volume would involve adjusting the axes lengths relative to each other.

(2) Cone:

The volume of a cone is $V = \frac{1}{3}\pi r^2 h$, where r is the radius of the base and h is the height.

The surface area is $A = \pi r(\sqrt{h^2 + r^2}) + \pi r^2$, which includes both the lateral surface and the base.

Minimizing the surface area for a cone involves balancing the radius and height, often leading to a cone where the slant height equals the base radius for optimal material use.

(3) Torus:

The volume of a torus (doughnut shape) depends on the major radius R and the minor radius r: $V= 2\pi^2 Rr^2$.

The surface area is $A=4\pi^2 Rr$.

Minimizing material use for a torus requires a balance between the major and minor radii.

(4) Prism:

For a prism, the volume is given by the base area B times the height h (i.e., V=Bh).

Minimizing surface area depends on the shape of the base and the height, which can vary depending on whether the base is a square, triangle, etc.

(5) Pyramid:

The volume of a pyramid is V=13Bh, where B is the

Table 1. Optimizing Geometric Shapes for Packaging: Volume and Minimum Surface Area for Material Efficiency

Shape	Volume Equation	Minimum Surface Area (Material)	Optimum Dimensions	Other Notes
Cylinder	$V = \pi r^2 h$	$A = 6\pi\left(\frac{V}{2\pi}\right)^{\frac{2}{3}}$	$r = \left(\frac{V}{2\pi}\right)^{\frac{1}{3}}; h = 2r$	Common in bottles, cans, and tubes. Optimal when height is twice the radius.
Sphere	$V = \frac{4}{3}\pi r^3$	$A = 4\pi\left(\frac{3V}{4\pi}\right)^{\frac{2}{3}}$	$r = \left(\frac{3V}{4\pi}\right)^{\frac{1}{3}}$	The most efficient shape in terms of surface area for a given volume, though rarely practical due to stacking and storage issues.
Cube	$V=a^3$	$A=6a^2$	$a = \sqrt[3]{V}$	A cube provides good efficiency in stacking and storing with uniform side lengths. The side length is the cube root of the volume for minimal surface area.
Rectangular Box	V=lwh	A=2lw+2lh+2wh	Varies by length l, width w, height h	Widely used in packaging due to flexibility in length, width, and height. The dimensions can be adjusted to minimize material while maximizing volume.
Ellipsoid	$V = \frac{4}{3}\pi abc$	Approximate: $A \approx 4\pi\left(\frac{ab+ac+bc}{3}\right)^{2/3}$	Varies by semi-principal axes a, b, c	Rarely used in standard packaging but could be considered for specialized containers due to potential material savings. An ellipsoid has semi-principal axes a, b, and c; finding the exact surface area formula involves approximations for most cases.
Cone	$V = \frac{1}{3}\pi r^2 h$	$A = \pi r^2(1+\sqrt{3})$	Depends on radius r and height h	Conical shapes are used in funnels and some bottles. Optimizing radius and height can reduce material cost. The surface area involves the slant height, making the minimization process more complex.
Torus	$V=2\pi^2 R r^2$	$A=4\pi^2 Rr$	$h = \sqrt{2}\,r$ or $r = \left(\frac{3V}{\pi\sqrt{2}}\right)^{\frac{1}{3}}$	Less common in packaging, but the shape could inspire innovative designs for stackable or modular containers. A torus (doughnut shape) minimizes surface area for certain configurations but is more complex to analyze geometrically.
Prism	V = Bh	Depends on the base shape	Depends on base area B and height h	Minimizing the surface area depends on the base shape and the height.
Pyramid	$V = \frac{1}{3}Bh$	$A = B + \frac{1}{2}Pl$	P is the perimeter of the base, l is the slant height	Prismatic shapes are practical for packaging, especially for elongated products. Minimizing surface area involves balancing the base area and slant height.

area of the base and h is the height.

The surface area A=B+12P depends on the base area B, the perimeter P, and the slant height l.

Minimizing the material used involves adjusting the base area and the slant height to achieve the least surface area for a given volume.

Notes on Minimizing Surface Area:

For complex shapes like ellipsoids and toruses, the minimization of surface area often involves more advanced calculus and approximations.

Spheres remain the most efficient shape, minimizing surface area for any given volume, followed by other shapes where the surface is balanced between different dimensions.

5.2 Use of Minimal Adhesives

To ensure that split-layer packaging is easily separable, minimal adhesives should be used to attach layers. This prevents the layers from becoming too difficult to separate during the recycling process. Instead, strategic sealing should be employed to prevent movement while ensuring easy separation[27]. The choice of adhesives used in split-layer packaging is important for both recyclability and environmental impact. Water-soluble adhesives, for example, can be used to attach layers in a way that allows them to be easily separated during the recycling process. Additionally, the use of biodegradable or compostable adhesives can further enhance the sustainability of split-layer packaging[28].

5.3 Strategic Sealing

Strategic sealing is essential in split-layer packaging to prevent movement of the layers while ensuring easy separation. Proper sealing techniques can help maintain the

Table 2. Comparison of Sealing Techniques

Sealing Technique	Advantages	Disadvantages	Applications and Material Compatibility	Environmental Impact
Heat Sealing[32]	Strong, airtight seal for thermoplastics Cost-effective for large-scale production High-speed sealing High seal strength Suitable for many types of plastic packaging	Requires heat (may affect contents), precise temperature control, and specialized equipment High energy consumption	Food packaging, pharmaceuticals Plastics, laminates	High energy consumption Recyclability depends on material
Cold Sealing[33]	Ideal for heat-sensitive products Low energy consumption High-speed sealing process Easy to implement in high-speed production lines Low cost	Weaker bond than heat sealing Special adhesives needed Adhesive may degrade in extreme conditions	Chocolates, bandages, snacks Flexible materials, paper	Adhesives complicate recycling
Ultrasonic Sealing[34,35]	Strong bond without external heat Energy-efficient High seal strength Reduces material waste	High initial equipment cost and complex machinery and maintenance Limited material compatibility Medium-speed sealing	Food and beverage packaging Thermoplastics, some films	Energy-efficient but high initial setup
Induction Sealing[32,36]	Tamper-evident Leak-proof High-speed process Non-contact sealing Strong seal Easily automated for high-speed bottling	Limited to closures with conductive material High equipment cost Limited application outside cap sealing	Liquid, food, pharmaceuticals Bottles, jars (with metal or foil seals)	Low waste generation, but foil hard to recycle
Crimp Sealing[32]	Simple and fast process Low cost No adhesives or heat required High-speed process Easy to implement and low-maintenance equipment	Limited to flexible materials like bags Weak seal under heavy load Not suitable for liquids Weaker seal compared to other methods	Flexible packaging for snacks, bread Paper, plastics	Minimal environmental impact, no extra materials used
Hot-Melt Adhesive Sealing[37]	Fast bonding Strong adhesion High-speed sealing Compatible with multi-materials Medium cost Suitable for high-speed production	Adhesive affects recyclability Adhesive may degrade in heat Requires heated equipment Adhesive may add bulk to packaging	Packaging boxes, cartons, bags Paper, plastics, multi-materials	Adhesive residue complicates recycling
Pressure-Sensitive Sealing[38]	No heat or specialized equipment Resealable Low cost Easy to implement and adjust	Weaker bond Affected by temperature and humidity Adhesive contaminates recycling Not suitable for high-barrier applications	Resealable packaging for snacks Flexible materials, some paper	Adhesive residue affects recycling
Shrink Wrapping Sealing[39]	Tight, tamper-evident seal Transparent for product visibility Low cost Suitable for irregularly shaped products High-speed process	Requires heat, may affect contents High energy consumption May not protect against moisture High initial setup cost for shrink tunnels	Food products, multipacks, books Plastics, some flexible films	Excessive plastic usage, not easily recyclable

integrity of the packaging while making it easier to separate the layers for recycling[29]. Various sealing techniques can be used in split-layer packaging, including heat sealing[29,30], ultrasonic sealing[29,30], and pressure-sensitive adhesives[31] (Table 2). Each method has its advantages and disadvantages, depending on the materials used and the intended application. For example, heat sealing can create a strong bond between layers, but it may not be suitable for heat-sensitive materials. Ultrasonic sealing, on the other hand, can create a secure seal without the need for adhesives or high temperatures, making it suitable for a wider range of materials[29].

Ultrasonic sealing is the most environmentally friendly packaging technique due to its low energy consumption, strong seal without adhesives, and minimal material waste, making it easier to recycle. Crimp sealing also ranks high, as it uses no heat or adhesives and generates minimal waste, but is limited to flexible packaging. Both methods are preferable over heat-based or adhesive-based techniques, which consume more energy and complicate recycling.

5.4 Minimal and Clear Labeling

Minimal and clear labeling is essential for the effective disposal and recycling of split-layer packaging. Labels should be concise and informative, providing essential information such as material types, separation instructions, and disposal methods. To further reduce environmental impact, manufacturers can eliminate the need for additional label materials by using embossed or laser printing directly on the packaging. This approach not only minimizes the use of labels and ensures they are easy to understand, even for consumers with limited knowledge of recycling practices, but also avoids adding unnecessary materials that could complicate the recycling process. Clear and minimal labeling, combined with techniques like embossing or laser printing, thus enhances consumer understanding and promotes efficient recycling, supporting the overall sustainability of split-layer packaging[40-43].

6 CASE STUDIES

Several case studies illustrate the potential benefits of split-layer packaging. These examples demonstrate how split-layer packaging can improve recycling rates, reduce landfill dependence, and contribute to climate action.

6.1 Case Study 1: Food Packaging

A major food packaging company implemented split-layer packaging for its products, which also provided clear labeling and disposal instructions, improving consumer compliance with recycling guidelines. The implementation of split-layer packaging in this case study resulted in a significant increase in recycling rates, with over 70% of the packaging materials being successfully recycled. The use of easily separable layers allowed for efficient sorting and processing, reducing the overall environmental impact of the packaging. Additionally, the company reported cost savings from reduced material complexity and improved consumer satisfaction with clear disposal instructions[44,45].

6.2 Case Study 2: Enhancing Recyclability through Innovative Cosmetics Packaging

The cosmetics industry faces the challenge of developing sustainable packaging that protects product integrity and minimizes environmental impact. One innovative approach gaining traction is split-layer packaging, which design improves recyclability, reduces environmental footprint, saves costs by simplifying material complexity, and enhances consumer satisfaction with clear disposal instructions[46,47]. In this case study, split-layer packaging increased recycling rates by 50%, with consumers finding it easier to separate and recycle materials. The success of this initiative also bolstered the company's reputation for sustainability. Sustainable packaging designs in the industry can be categorized into circular design for technical cycles, circular design for biological cycles, and linear reduction strategies[48]. For example, Unilever's compressed deodorants use 25% less packaging material, demonstrating the potential of linear reduction[48]. The industry is also exploring renewable and biodegradable materials to enhance sustainability[49,50].

6.3 Case Study 3: Beverage Packaging

A beverage company introduced split-layer packaging for its bottled products, featuring an inner plastic bottle and an outer cardboard sleeve. This design may result in a 60% reduction in the company's packaging waste sent to landfills. The easily separable design facilitated efficient recycling of both the plastic bottle and the cardboard sleeve. Additionally, the company received positive feedback from consumers who appreciated the clear disposal instructions and the environmentally friendly design of the packaging. Furthermore, Coca-Cola introduced PlantBottle™ packaging, a fully recyclable plastic bottle partially made from plant-based materials, to promote the use of renewable resources[48].

7 TREND AND SUPPORT FOR MORE SUSTAINABLE PACKAGING AND RECYCLING

7.1 Sustainable Materials in Packaging

The use of sustainable materials in packaging is a growing trend aimed at reducing environmental impact. Biodegradable and compostable materials, such as plant-based plastics, are gaining popularity as alternatives to traditional plastics. These materials can break down more easily in the environment, reducing the accumulation of plastic waste. The integration of sustainable materials into split-layer packaging can further enhance its environmental benefits, making it a more attractive option for consumers and manufacturers alike[51].

7.2 Regulatory Frameworks and Policies

Government regulations and policies play a crucial role in promoting sustainable packaging practices. Initiatives such as Extended Producer Responsibility (EPR) require manufacturers to take responsibility for the entire lifecycle of their products, including disposal and recycling. These policies encourage companies to adopt more sustainable packaging solutions, such as split-layer packaging, to reduce waste and improve recycling rates. Additionally, regulations on single-use plastics are prompting businesses to explore innovative packaging alternatives that align with sustainability goals. In Europe there is plastic tax over un-recycled plastic starting from January 2021 as well as the New Circular Economy Action Plan requires all plastic packaging in EU market should be reusable or recyclable by

2023. This regulatory landscape creates both opportunities and challenges for the widespread adoption of split-layer packaging across various industries[52].

7.3 Consumer Behavior and Awareness

Consumer behavior significantly influences the success of sustainable packaging initiatives. Increasing awareness of environmental issues and the impact of plastic waste on the planet has led to a demand for more sustainable packaging options. Educating consumers about the benefits of split-layer packaging and providing clear disposal instructions can enhance participation in recycling programs. Understanding consumer preferences and behaviors is essential for companies aiming to implement effective sustainable packaging strategies[18,24].

7.4 Technological Innovations in Recycling

Advancements in recycling technologies are critical for improving the efficiency and effectiveness of recycling processes. Innovations such as automated sorting systems, AI-driven waste management solutions[53], and chemical recycling technologies are transforming the recycling landscape. These technologies can enhance the sorting and processing of split-layer packaging materials, further improving recycling rates and reducing environmental impact. Investing in research and development for new recycling technologies is essential for addressing the challenges posed by multilayer packaging waste[54].

7.5 Future Prospects and Industry Trends

The future of sustainable packaging is being shaped by innovations in materials and technology which further driven by government policies promoting the EPR[55]. Biodegradable and compostable materials , along with smart packaging technologies (such as RFID tags and QR codes), can enhance the functionality and sustainability of split-layer packaging[55-58].

8 CONCLUSIONS

Split-layer packaging presents a promising alternative to traditional multilayer packaging by simplifying recycling, reducing costs, and lowering emissions. To foster its adoption, industry collaboration and standardization are essential, along with innovative designs and clear labeling.

Challenges in Scaling Up: However, the transition to split-layer packaging faces challenges, including the need for industry-specific adaptations, potential increased costs for manufacturers, and the necessity for new recycling infrastructure. Different industries may require tailored solutions to meet specific regulatory standards and consumer expectations, which could slow the broader adoption of this packaging solution.

Alignment with Sustainability Goals: Split-layer packaging aligns with global sustainability goals by contributing to waste reduction, enhancing recycling efforts, and supporting circular economy initiatives. By facilitating the recycling of materials and reducing reliance on single-use plastics, split-layer packaging can play a critical role in meeting international environmental targets.

Supportive legislation, economic incentives, investment in research, improved recycling infrastructure, and effective monitoring are also necessary. Engaging all stakeholders will ensure the successful implementation of split-layer packaging, leading to sustainable solutions and a climate-friendly future.

Acknowledgements
Not applicable.

Conflicts of Interest
The authors declared no conflict of interest.

Author Contribution
The submitted work represents a collective effort by the authors. Yenni Ciawi conceived the concept of split-layer packaging and also edited the manuscript. Silvia Gabrina Tonyes handled the editing of the manuscript, while Ni Made Utami Dwipayanti provided contributions in reviewing and editing the manuscript.

Abbreviation List
EPR, Extended Producer Responsibility

References

[1] Kaiser K, Schmid M, Schlummer M. Recycling of Polymer-Based Multilayer Packaging: A Review. *Recycling*, 2017; 3: 1.[DOI]
[2] Mujtaba M, Lipponen J, Ojanen M et al. Trends and challenges in the development of bio-based barrier coating materials for paper/cardboard food packaging; a review. *Sci Total Environ*, 2022; 851: 158328.[DOI]
[3] Ding Q, Zhu H. The Key to Solving Plastic Packaging Wastes: Design for Recycling and Recycling Technology. *Polymers*, 2023; 15: 1485.[DOI]
[4] Accorsi R, Baruffaldi G, Manzini R. A Closed-Loop Packaging Network Design Model to Foster Infinitely Reusable and Recyclable Containers in Food Industry. *Sustain Prod Consump*, 2020; 24: 48-61.[DOI]
[5] Dilkes-Hoffman LS, Lane JL, Grant T et al. Environmental impact of biodegradable food packaging when considering food waste. *J Clean Prod*, 2018; 180: 325-334.[DOI]
[6] Atiwesh G, Mikhael A, Parrish CC et al. Environmental Impact of Bioplastic Use: A Review. *Heliyon*, 2021; 7: e07918.[DOI]
[7] Saraswati AW. Multilayer Plastic: The Hardest Recycled Material - Green Info. Greeneration Foundation. Accessed July 17 2024. Available at:[Web]
[8] Ziani K, Ioniță-Mîndrican CB, Mititelu M et al. Microplastics: A Real Global Threat for Environment and Food Safety: A State of the Art Review. *Nutrients*, 2023; 15: 617.[DOI]
[9] Soares CTDM, Ek M, Östmark E et al. Recycling of multi-

material multilayer plastic packaging: Current trends and future scenarios. *Resour Conserv Recy*, 2022; 176: 105905.[DOI]

[10] Bauer AS, Tacker M, Uysal-Unalan I et al. Recyclability and Redesign Challenges in Multilayer Flexible Food Packaging-a Review. *Foods*, 2021; 10: 2702.[DOI]

[11] Coates GW, Getzler YDYL. Chemical recycling to monomer for an ideal, circular polymer economy. *Nat Rev Mater*, 2020; 5: 501-516.[DOI]

[12] Lamtai A, Elkoun S, Robert M et al. Mechanical Recycling of Thermoplastics: A Review of Key Issues. *Waste*, 2023; 1: 860-883.[DOI]

[13] Niaounakis M. Recycling of Flexible Plastic Packaging. William Andrew: Oxford, Britain, 2020.[DOI]

[14] Walker TW, Frelka N, Shen Z et al. Recycling of multilayer plastic packaging materials by solvent-targeted recovery and precipitation. *Sci Adv*, 2020; 6: eaba7599.[DOI]

[15] Gilani Z. Enzymatic Depolymerization and Recycling: Using Enzymes to Convert Linear Waste Streams into Circular Supply Chains. Cleantech Group Perspectives. 2022 [cited 2024 Jul 30]. Available at:[Web]

[16] Lin Y, Severson MH, Nguyen RT et al. Economic and environmental feasibility of recycling flexible plastic packaging from single stream collection. *Resour Conserv Recy*, 2023; 192: 106908.[DOI]

[17] Lamichhane G, Acharya A, Marahatha R et al. Microplastics in environment: global concern, challenges, and controlling measures. *Int J Environ Sci Technol*, 2023; 20: 4673-4694.[DOI]

[18] Gürlich U, Kladnik V, Tacker M et al. Packaging Design for Recycling Packaging Design for Recycling a Global Recommendation for "Circular Packaging Design" All Rights Reserved. Published online 2021.

[19] Anukiruthika T, Sethupathy P, Wilson A et al. Multilayer Packaging: Advances in Preparation Techniques and Emerging Food Applications. *Comp Rev Food Sci Food Safe*, 2020; 19: 1156-1186.[DOI]

[20] Procházka R, Valíček J, Harničárová M et al. Collection of Plastic Packaging of Various Types: Sorting of Fractions of Plastic Waste Using Both Automated and Manual Modes. *IEEE Access*, 2024; 12: 44244-44261.[DOI]

[21] Abatan A, Lottu OA, Ugwuanyi ED et al. Sustainable Packaging Innovations and Their Impact on Hse Practices in the Fmcg Industry. *Magna Sci Adv Res Rev*, 2024; 10: 379-391.[DOI]

[22] Kassab A, Al Nabhani D, Mohanty P et al. Advancing Plastic Recycling: Challenges and Opportunities in the Integration of 3D Printing and Distributed Recycling for a Circular Economy. *Polymers*, 2023; 15: 3881.[DOI]

[23] Zhao X, Korey M, Li K et al. Plastic waste upcycling toward a circular economy. *Chem Eng J*, 2022; 428: 131928.[DOI]

[24] Moshood TD, Nawanir G, Mahmud F et al. Sustainability of biodegradable plastics: New problem or solution to solve the global plastic pollution? *Curr Res Green Sust Chem*, 2022; 5: 100273.[DOI]

[25] Allen C. The Economic and Environmental Benefits of Efficient Waste Management. Advances in Recycling & Waste Management. Accessed July 30 2024. Available at:[Web]

[26] Liu X, Li S, Chen W et al. Assessing Greenhouse Gas Emissions and Energy Efficiency of Four Treatment Methods for Sustainable Food Waste Management. *Recycling*, 2023; 8: 66.[DOI]

[27] Walther T. Whitepaper Adhesives and Recycling: Strategies for Improvement. Accessed July 30 2024. Available at:[Web]

[28] Packham DE. The environmental impact of adhesives. In: Eco-Efficient Construction and Building Materials. *Elsevier*, 2014; 338-367.[DOI]

[29] Bamps B, Buntinx M, Peeters R. Seal Materials in Flexible Plastic Food Packaging: A Review. *Packag Technol Sci*, 2023; 36: 507-532.[DOI]

[30] Demircan B, Velioglu YS. Revolutionizing single-use food packaging: A comprehensive review of heat-sealable, water-soluble, and edible pouches, sachets, bags, or packets. *Crit Rev Food Sci*, 2023; 2023: 1-21.[DOI]

[31] Mapari S, Mestry S, Mhaske ST. Developments in pressure-sensitive adhesives: A review. *Polym Bull*, 2021; 78: 4075-4108.[DOI]

[32] Ilhan I, Turan D, Gibson I et al. Understanding the factors affecting the seal integrity in heat sealed flexible food packages: A review. *Packag Technol Sci*, 2021; 34: 321-337.[DOI]

[33] Adhiaman AS, Ramalakshmi K, Madhushalini D. Industry-Ready Active Packaging Technologies in Food Sector. *IJCRR*, 2021; 13: 01-06.[DOI]

[34] Koo Sin Lin C, Oehm L, Majschak J. Innovative focused ultrasound-based sealing method of flexible packaging films-Principles and characteristics. *Packag Technol Sci*, 2020; 33: 397-405.[DOI]

[35] Li B, Zhong M, Sun Y et al. Recent advancements in the utilization of ultrasonic technology for the curing of processed meat products: A comprehensive review. *Ultrason Sonochem*, 2024; 103: 106796.[DOI]

[36] Yam KL. The Wiley Encyclopedia of Packaging Technology (3rd ed). John Wiley & Sons: Hoboken, N.J., USA, 2009.

[37] Sastri VR. Three-Dimensional Printing, Wearables, Medical Textiles, Adhesives, and Coatings. In: Plastics in Medical Devices. *Elsevier*, 2022; 2022: 381-421.[DOI]

[38] Petrie EM. Handbook of Adhesives and Sealants (3rd ed). McGraw Hill: New York, USA, 2021.

[39] Jiang SJ, Huang JY. The Technology and Application of Shrink Packaging. 2015 International Conference on Material Science and Applications (ICMSA-15), Suzhou, China, June 13-14, 2015.

[40] Meis-Harris J, Klemm C, Kaufman S et al. What is the role of eco-labels for a circular economy? A rapid review of the literature. *J Clean Prod*, 2021; 306: 127134.[DOI]

[41] Burrows SD, Ribeiro F, O'Brien S et al. The Message on the Bottle: Rethinking Plastic Labelling to Better Encourage Sustainable Use. *Environ Sci Policy*, 2022; 132: 109-118.[DOI]

[42] Hu Y, Frank B, Lu Z. Market success through recycling programs: Strategic options, consumer reactions, and contingency factors. *J Clean Prod*, 2022; 353: 131003.[DOI]

[43] Latkin CA, Dayton L, Yi G et al. The (Mis)Understanding of the Symbol Associated with Recycling on Plastic Containers in the US: A Brief Report. *Sustainability*, 2022; 14: 9636.[DOI]

[44] Paiva CL, Ugaya CML. Environmental impacts assessment in

packaging and its contribution to reducing food waste. *Clean Circ Bioeconomy*, 2024; 8: 100083.[DOI]

[45] Versino F, Ortega F, Monroy Y et al. Sustainable and Bio-Based Food Packaging: A Review on Past and Current Design Innovations. *Foods*, 2023; 12: 1057.[DOI]

[46] Dube M, Dube S. Towards Sustainable Color Cosmetics Packaging. *Cosmetics*, 2023; 10: 139.[DOI]

[47] Gatt IJ, Refalo P. Reusability and recyclability of plastic cosmetic packaging: A life cycle assessment. Resources, *Resour Cons Recy Adv*, 2022; 15: 200098.[DOI]

[48] Steenis ND, Van Der Lans IA, Van Herpen E et al. Effects of sustainable design strategies on consumer preferences for redesigned packaging. *J Clean Prod*, 2018; 205: 854-865.[DOI]

[49] Cinelli P, Coltelli M, Signori F et al. Cosmetic Packaging to Save the Environment: Future Perspectives. *Cosmetics*, 2019; 6: 26.[DOI]

[50] Markevičiūtė Z, Varžinskas V. Smart Material Choice: The Importance of Circular Design Strategy Applications for Bio-Based Food Packaging Preproduction and End-of-Life Life Cycle Stages. *Sustainability*, 2022; 14: 6366.[DOI]

[51] Boz Z, Korhonen V, Koelsch Sand C. Consumer Considerations for the Implementation of Sustainable Packaging: A Review. *Sustainability*, 2020; 12: 2192.[DOI]

[52] WTS Global. Plastic Taxation in Europe: Update 2023. Accessed August 3 2024. Available at:[Web]

[53] Fang B, Yu J, Chen Z et al. Artificial intelligence for waste management in smart cities: A review. *Environ Chem Lett*, 2023; 21: 1959-1989.[DOI]

[54] Pilapitiya PGCNT, Ratnayake AS. The world of plastic waste: A review. *Clean Mater*, 2024; 11: 100220.[DOI]

[55] Salgado PR, Di Giorgio L, Musso YS et al. Recent Developments in Smart Food Packaging Focused on Biobased and Biodegradable Polymers. *Front Sustain Food Syst*, 2021; 5: 630393.[DOI]

[56] Patel KR. Harmonizing Sustainability, Functionality, and Cost: Navigating Responsible Packaging Innovations in Modern Supply Chains. *AJEMB*, 2023; 2: 287-300.[DOI]

[57] Pirzadah TB, Malik B, Bhat RA et al. Bioresource Technology: Concept, Tools and Experiences (1st ed). Wiley: Hoboken, USA, 2022.

[58] ThePackHub. Packaging Innovation. Accessed August 1 2024. Available at:[Web]