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Optimizing bubble tea packaging sustainability in Taipei: A life cycle assessment and multi-objective optimization approach for circular economy integration

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ABSTRACT

The rapid growth of the global bubble tea market, projected to reach USD 3.72 billion by 2034, has intensified concerns over packaging-related environmental impacts. This study integrates a demand-driven LCA framework with multi-objective optimization to identify sustainable packaging design strategies across the product life cycle. The model evaluates economic and environmental indicators using established LCA methods and databases. The analysis yields 9 Pareto-optimal solutions, revealing that reusable PP packaging achieves lower impacts in several environmental categories but requires at least 120 uses to justify manufacturing burdens, with optimal performance beyond 300 uses. Once usage exceeds 100 uses, design priorities shift from material selection toward durability and logistics in reusable systems. Industry feedback confirms operational challenges including consumer perception-driven retirement, infrastructure constraints, and cost structure barriers. This study advances methodological innovation by integrating real-world reuse dynamics, usage frequency dependencies, and stakeholder insights to bridge the gap between technical optimization and practical implementation.

1. Introduction

The global bubble tea market is expected to increase with a compound annual growth rate of 8.1% from 2024 to 2034 and to reach the value of 3.72 billion US dollars by 2034 (News, 2025). However, this market expansion might also lead to a significant increase in packaging waste. In Taiwan, a region with exceptionally high bubble tea consumption, over 4 billion cups are consumed annually, equating to >150 cups per capita annually (Ministry of Economic Affairs, 2022). Additionally, there are 12 bubble tea stores per square kilometer, with the number of stores growing at a rate of 5.8% between 2015 and 2023 (Ministry of Economic Affairs, 2024). In response to rapidly rising concerns over the environmental impacts of bubble tea packaging, this research aims to explore strategies for designing more sustainable bubble tea packaging solutions and industry in Taiwan. While previous Life Cycle Assessment (LCA) studies often focus on individual packaging products, this research adopts a demand-driven perspective, evaluating packaging impacts across the entire bubble tea life cycle stages. In doing so, this study identifies high-potential design strategies and supports informed decision making that align both with environmental sustainability goals and evolving market demand.

Previous LCA studies tend to focus mainly on evaluating supply-side environmental impacts and informing production-centered decision-making (Han et al., 2025; Sanyé-Mengual and Sala, 2022; Van Roijen and Miller, 2022). They usually identify environmental hotspots for specific packaging types or production stages (Kaiser et al., 2022; Kan and Miller, 2022; Kositcharoenkul et al., 2025; Zhou et al., 2023). While such studies offer valuable insights for improving upstream efficiency, they often overlook the dynamic influence of consumer demand, usage behavior, and market-driven factors on environmental outcomes, thereby limiting their ability to capture circularity-oriented strategies that align with real-world consumption patterns (Han et al., 2025; Jerome et al., 2022; Van Roijen and Miller, 2022). Supply-oriented LCA typically relies on a static functional unit to identify hotspots within specific production stages (Bamber et al., 2020; Majeau-Bettez et al., 2018) and assumes linear scaling with fixed input/output coefficients (Arvidsson et al., 2018; Earles et al., 2013), implying that a change in a product's design does not influence the total market volume or consumer demand. Consequently, although such studies

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provide detailed insights into the efficiency of a single unit (e.g., one container), they fail to capture how "high-consumption markets" and the magnitude of demand drive total environmental impacts (Earles et al., 2013; Kjaer et al., 2016). Thus, this perspective may lead to suboptimal outcomes in high-consumption markets like Taiwan.

This study applies multi-objective optimization within an LCA framework to support decision-making in bubble tea packaging design. Multi-objective approaches are suited to addressing the "decision-making conundrum" where functional improvements often conflict with environmental or economic goals (Ibn-Mohammed et al., 2024; Parece et al., 2025). By incorporating multiple objectives, this approach can systematically explore trade-off relationships tensions in packaging design while accounting for methodological uncertainties inherent in LCA studies (Ibn-Mohammed et al., 2024; Sienkiewicz et al., 2024).

This study contributes to sustainable bubble tea packaging design by integrating demand-driven LCA with multi-objective optimization to support practical decision-making in Taiwan's high-consumption market. Unlike conventional supply-oriented LCA, this research simulates various packaging designs under market demand conditions within an optimization model, capturing optimal design combinations. This study identifies packaging strategies by adopting a Satisficing Framework that balances environmental performance, economic viability, and market feasibility.

2. Methods

This paper discusses how bubble tea packaging can be designed more sustainable from a demand-driven perspective by (1) defining the system boundary and functional unit to establish the assessment scope, (2) identifying packaging design alternatives across single-use and reusable categories, (3) quantifying environmental and economic impacts through LCA, and (4) formulating a multi-objective optimization model to identify Pareto-optimal packaging solutions that balance competing objectives.

2.1. System boundary and functional unit

This study adopts a cradle-to-grave system boundary that encompasses all major lifecycle stages (Fig. 1). The upstream boundary begins with the extraction and production of raw materials, including paper

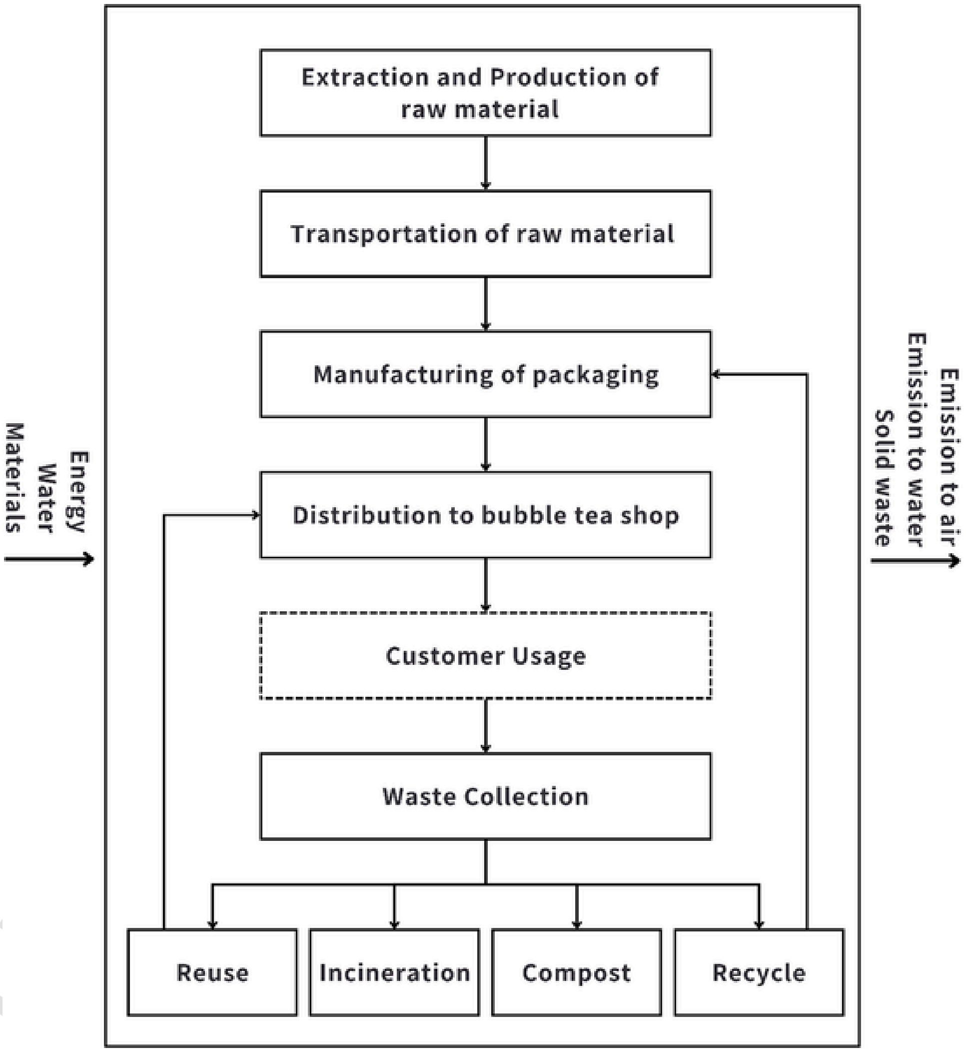

Fig. 1. System boundary of sustainable bubble tea packaging design.
This figure illustrates the complete life cycle system boundary for sustainable bubble tea packaging design. It shows the flow from raw material extraction through production, transportation, manufacturing, and distribution to bubble tea shops, followed by customer usage and waste management. The dashed line around the customer usage stage indicates that this phase is excluded from the environmental impact assessment, as it involves only consuming the bubble tea and does not contribute to environmental impacts within the scope of this study.

pulp and plastic resins, such as polylactic acid (PLA), polyethylene terephthalate (PET), high-density polyethylene (HDPE), polystyrene (PS), or polypropylene (PP), as well as bagasse fibers for bio-based alternatives. This upstream stage includes the transportation of raw materials to manufacturing facilities. The packaging manufacturing stage covers cup body fabrication, interior liner application for paper cups, and lid production. Following manufacturing, distribution to bubble tea shops accounts for logistics from production facilities to retail locations, with an estimated transportation distance of 90 km. The downstream boundary addresses waste collection and subsequent end-of-life scenarios including reuse for returnable cups, incineration with energy recovery, composting for biodegradable materials, and recycling with material recovery credits. Waste collection from disposal points to treatment facilities is estimated at 12 km. For the reuse pathway, the transportation distance encompasses collection from bubble tea shops to washing centers and redistribution back to shops, totaling approximately 40 km per cycle. The distribution distance is estimated based on the starting point and ending point provided by the industry partner.

The functional unit is defined as one bubble tea packaging, which serves as the basis for quantifying and comparing life cycle impacts across all design alternatives. This functional unit enables direct comparison of environmental and economic performance on a per-cup basis, regardless of packaging type or material composition.

2.2. Packaging design alternative

The packaging design alternatives are structured as a decision framework encompassing three decision layers: usage scenario, material selection, and end-of-life scenario (Fig. 2). The combination of these three decision layers yields eighteen distinct packaging design configurations, all standardized to a 700 mL capacity suitable for cold bubble tea beverages.

The first decision layer addresses the usage scenario, which determines whether the packaging follows a single-use or reusable pathway. Single-use packaging is consumed once and then discarded, while reusable packaging undergoes multiple use cycles with washing between uses before eventual disposal.

The second decision layer focuses on material selection, which varies by usage scenario. For single-use packaging, two primary categories are available: paper cups and plastic cups. Paper cups consist of three components, each requiring separate material decisions. The cup body is made from bleached board, providing structural integrity. The cup liner ensures liquid resistance through either PLA as a bio-based option or LDPE as a conventional petroleum-based option. The lid has five material choices, including PLA, PET, HDPE, PS, and PP. Plastic cups consist of a monolithic cup body with integrated lid, available in five materials: HDPE, PS, PP, PET, and PLA. For reusable packaging, three cup types are considered: PP cups, HDPE cups, and bagasse cups, each designed as integrated cup-lid systems suitable for repeated use cycles.

The third decision layer deals with the end-of-life scenario, determining the waste management pathway for each material component. Single-use packaging components face a decision between recycling and incineration. Reusable packaging components have three potential pathways: reuse for continued service life, recycling at the end of product life, or incineration.

2.3. Life cycle inventory

The life cycle inventory was compiled in compliance with ISO 14040/14044 guidelines, using both primary and secondary data sources. Primary data on material quantities were obtained through di-

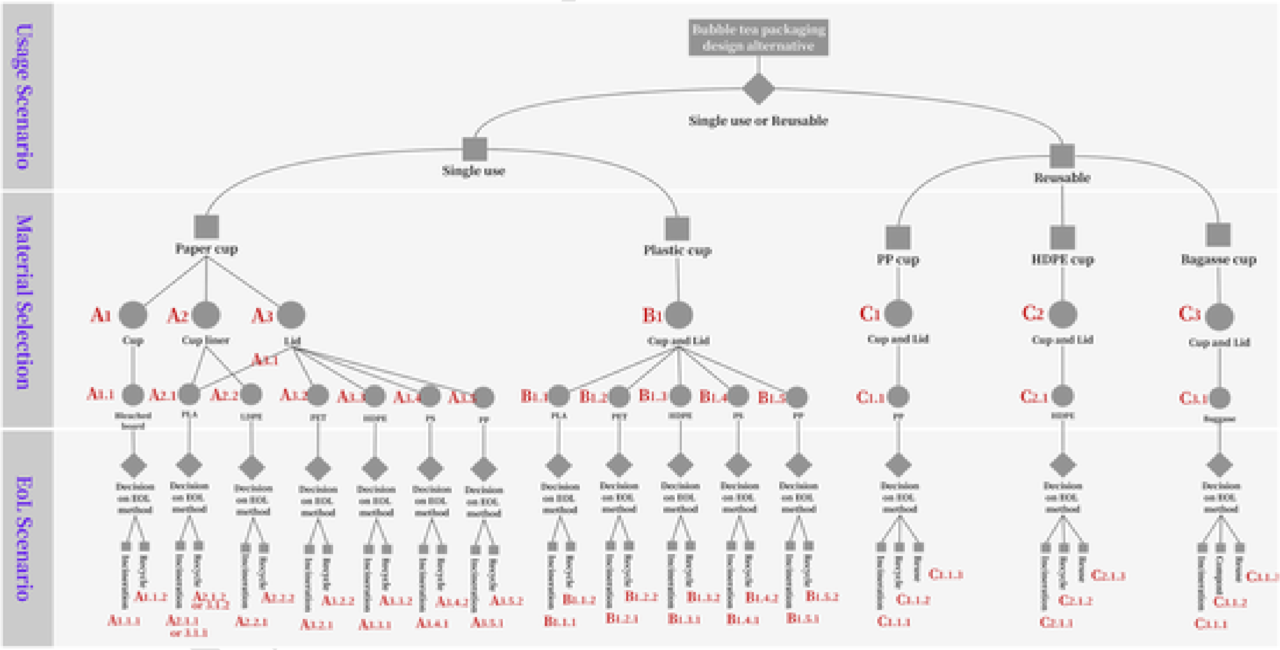

Fig. 2. Bubble tea packaging design alternatives.
This hierarchical decision tree systematically maps bubble tea packaging alternatives from initial design choices to the end-of-life management. The top node represents the fundamental choice between single-use and reusable systems, branching into three main categories: paper cups (Category A), plastic cups (Category B), and reusable cups (Category C). The paper cup system comprises three components: cup body (A1), liner options (A2), and lid materials (A3), with lids subdividing into five alternatives, PLA, PET, HDPE, PS, and PP (A3.1-A3.5). The plastic cup system offers five material options (B1.1-B1.5): PLA, PET, HDPE, PS, and PP. The reusable category includes PP cups (C1), HDPE cups (C2), and bagasse cups (C3). Each material option terminates in diamond-shaped nodes representing End-of-Life (EOL) pathways for incineration or recycling. Uniquely, reusable options include an additional "Reuse" pathway (C1.1.3, C2.1.3, C3.1.3) quantifying multiple-use cycles before disposal. This structure visualizes all 47 decision variables across the three packaging categories, providing a comprehensive framework for bubble tea packaging design and management.

rect measurement of packaging samples and consultations with Taipei-based bubble tea packaging suppliers. Secondary data for upstream processes were sourced from the Ecoinvent 3.9.1 database, including raw material extraction, manufacturing, energy generation, transportation, and end-of-life treatment (Huang, 2026). Datasets representing East Asian or global average conditions were prioritized when Taiwan-specific data were unavailable.

Cost data were obtained from supplier quotations and published industry reports, expressed in New Taiwan Dollars (NTD) per functional unit. Economic impact was assessed through total cost accounting. Total costs were aggregated from material procurement, processing, transportation, and end-of-life management based on current market prices and municipal fee structures in Taiwan.

2.4. Life cycle impact assessment

This study selects six impact categories based on their demonstrated relevance to packaging systems. (1) Global Warming Potential (GWP) was prioritized as packaging materials contribute approximately 40% of the total carbon footprint in tea-based beverages (Zhang et al., 2023). GWP represents the most universally assessed indicator for beverage packaging comparison (Brock and Williams, 2020). (2) Abiotic Resource Depletion (Fossil) is critically important given that fossil resource depletion accounts for 95.47% of the environmental burden in plastic packaging production. Petroleum-based polymer manufacturing constitutes the dominant hotspot in beverage container life cycles (Brock and Williams, 2020; Khairi et al., 2025). (3) Marine Aquatic Ecotoxicity exhibits the highest absolute magnitude of potentially harmful effects during plastic production (Stefanini et al., 2021). (4) Eutrophication Potential and (5) Acidification Potential represent significant impact pathways in plastic waste management systems, as acidification is primarily linked to sulfur oxide emissions during production processes (Lee et al., 2022). (6) Human Toxicity demonstrates high variability and substantial impact in food packaging assessments, particularly in end-of-life disposal scenarios (Stefanini et al., 2021; Zhao et al., 2023).

Environmental impacts were characterized using the CML-IA baseline method to translate inventory flows into environmental impact scores and enable comparison across materials with different emission profiles.

2.5. Optimization model formulation

This section solves the optimization model that integrates LCA with operational constraints to identify a Pareto-optimal packaging portfolio across economic and environmental objectives. While the functional unit for LCA impact characterization is defined as one bubble tea packaging on a per-cup basis, the optimization model operates at the system scale by simulating packaging choices required to meet annual market demand.

2.5.1. Decision variables

According to packaging design alternatives in Fig. 2, this optimization model determines 47 decision variables structured across three main packaging categories: paper cups (20 variables), single-use plastic cups (15 variables), and reusable cups (12 variables). Each category encompasses decisions at multiple levels, including material selection for cup components (body, liner, and lid), the choice of specific materials (PLA, PET, HDPE, PS, PP, or bagasse), and end-of-life treatment scenarios (incineration, recycling, or reuse).

2.5.2. Objective function

The optimization model minimizes seven objectives encompassing both economic and environmental dimensions: Cost (NTD), Global Warming Potential (kg CO_2 eq), Abiotic Resource Depletion (MJ), Marine Aquatic Ecotoxicity (kg 1,4-DB eq), Acidification Potential (kg SO_2 eq), Eutrophication Potential (kg PO_4 eq), and Human Toxicity (kg 1,4-DB eq). Each objective function is formulated as a linear aggregation (Eq. (1)):

$$f_k(x) = \sum_{i=1}^{47} c_{k,i} \times x_i \tag{1}$$

where $c_{k,i}$ denotes the coefficient associated with decision variable i under objective k. An important methodological consideration is that certain coefficients assume negative values, particularly for recycling activities. These negative values reflect environmental credits from offsetting virgin material production impacts.

Eq. (2) seeks to simultaneously minimize all seven objectives:

$$\min_x F(x) = \left[f_1(x), f_2(x), f_3(x), f_4(x), f_5(x), f_6(x), f_7(x)\right] \tag{2}$$

where $f_1(x)$ represents total cost; $f_2(x)$, Global Warming Potential; $f_3(x)$, Abiotic Depletion; $f_4(x)$; Marine Ecotoxicity; $f_5(x)$, Acidification; $f_6(x)$, Eutrophication; and $f_7(x)$, Human Toxicity. Eq. (2) defines a vector optimization problem where the solution concept is Pareto optimality rather than a single global optimum.

2.5.3. Constraints

The mathematical formulation incorporates a constraint structure ensuring both physical feasibility and operational realism (Eq. (3)). Eq (3) ensures that the total number of cup servings, including both initial uses and subsequent reuse events from reusable cup systems, meets or exceeds the annual demand of one million units:

$$\sum_i A_{1.1} + \sum_{i=1}^{5} B_{1,\ i} + \sum_{j=1}^{3} C_{j,\ 1} + \sum_{j=1}^{3} C_{j,\ 1,3} \geq 1,000,000 \tag{3}$$

where the total servings are supplied by paper cups manufactured ($A_{1,1}$), single-use plastic cups manufactured ($B_{1,i}$ for materials i = PLA, PET, HDPE, PS, PP), reusable cups manufactured ($C_{j,1}$ for materials j = PP, HDPE, bagasse), and reuse events from reusable cups ($C_{j,1,3}$).

End-of-life balance equations, represented by Eq. (4), guarantee that the total quantity of each material manufactured is completely allocated between disposal and recycling pathways:

$$x_{disposal} + x_{recycling} = x_{total} \tag{4}$$

This mass balance constraint ensures that every cup manufactured is accounted for at the end-of-life, either through disposal (landfill or incineration) or recycling.

Recycling rate constraints impose an upper bound of 89%, based on statistics from Taiwan Ministry of Environment, on the proportion of materials diverted to recycling. This reflects realistic limitations in collection infrastructure, sorting capabilities, and material quality degradation (Eq. (5)):

$$x_{recycling} \leq 0.89 \ \times x_{total} \tag{5}$$

Reuse capacity constraints acknowledge the finite operational lifetime of reusable cup systems, with maximum use cycles varying by material durability. These constraints are formulated in Eq. (6):

$$C_{j,\ 1,3} \leq L_j \times C_{j,1} \tag{6}$$

where L_j represents the maximum number of reuse cycles for material j: PP cups can withstand up to 240 uses ($L_j = 240$), HDPE cups up to 180 uses ($L_j = 180$), and bagasse cups up to 120 uses ($L_j = 120$).

Finally, non-negativity constraints presented in Eq. (7) ensure all decision variables assume physically meaningful values:

$$x_i \geq 0 \ \forall i \tag{7}$$

2.5.4. Solution algorithm: Weighted sum method

Multi-objective optimization requires normalizing objectives measured in different units and scales. This study employs ideal-nadir normalization to transform each objective to a standardized [0, 1] interval based on the achievable range within the feasible region. The ideal point represents the best achievable value when each objective is minimized individually, and the nadir point represents the maximum value of each objective across all individual optima.

To compute Pareto-optimal solutions, this study adopts the weighted sum method and scalarizes the multi-objective optimization problem through a convex combination of normalized objectives. For a weight vector $w = (w_1, w_2, \ldots, w_7)$ satisfying $w_k \geq 0$ and $\sum_{k=1}^{7} w_k = 1$, the scalarized problem is shown in Eq. (8). All resulting MILP problems are solved using the CBC solver through Python's PuLP library.

$$min_x \sum_{k=1}^{7} w_k \times \bar{f}_k(x) \ \ subject\ to\ constraints\ (3)\ to\ (7) \tag{8}$$

Each weight $w_k$represents the relative importance of objective k, with larger values assigning greater priority to that objective.

2.5.5. Industry interview

This study employed a semi-structured interview to validate quantitative modeling findings and identify practical implementation challenges. The interviewees were two representatives from reusable packaging solution provider operating in Taiwan's bubble tea market. The interview guide covered three main categories: the optimal solutions, practical feedback on reusable packaging, and potential strategies for enhancing the implementation of reusable packaging.

3. Results and discussions

3.1. LCA results

To examine how usage frequency affects environmental performance, the LCA was extended to analyze bubble tea packaging at 1, 25, 50, 100, 150, 200, 250, and 300 uses. Fig. 3 presents impacts per-cup for four designs: Design 1 (single-use paper), Designs 14 and 15 (single-use plastic), and Design 16 (reusable PP). Single-use designs (1, 14, 15) maintain constant per-cup impacts across all usage levels, as each use requires manufacturing a new package. Design 16, however, demonstrates markedly different behavior across the cost and six environmental objectives, with outcomes divided into two distinct categories based on whether sufficient reuse can overcome its initial manufacturing burden.

Three objectives demonstrate that Design 16 can match or exceed the best-performing alternatives with sufficient usage. Global warming potential shows the clearest success: Design 16 begins approximately 7.3 times worse than Design 1, but achieves parity with Design 15′s performance by 120 uses. Fossil fuel depletion exhibits the fastest payback, with Design 16 becoming superior by 25–30 uses and ultimately performing 46% better than Design 1 at 200+ uses, making it the most efficient design in this category. Marine ecotoxicity requires the longest commitment at 300–350 uses to match Design 15′s performance, beginning 15.7 times worse but eventually converging at approximately 50 kg 1,4-DB equivalent.

In contrast, three objectives reveal inherent material advantages in Design 15 that Design 16 cannot overcome regardless of usage frequency. Acidification shows Design 16 starting 35.8 times worse than Design 15 and, despite improving 36% over Design 1 by 50 uses, remaining 3.2 times worse than Design 15 even at 400 uses. Eutrophication demonstrates the most striking gap: while Design 16 improves to match Design 14 by 100 uses, Design 15 exhibits unique negative values indicating actual nutrient removal benefits. Human toxicity maintains a persistent 1.3-fold advantage for Design 15 throughout all usage levels, suggesting fundamental differences in material toxicity profiles independent of usage patterns. Cost follows a similar pattern, starting 10 times higher than Design 14 but achieving parity with Design 1 around 50 uses and decreasing to 4.91 NTD by 100 uses. However, Design 16 never overcomes Design 14 and 15 in cost.

This analysis reveals a critical threshold: Design 16 requires a minimum of 120 uses to justify its higher manufacturing burden, with optimal performance emerging beyond 300 uses. Below 60 uses, Design 16 represents a net environmental harm compared to all alternatives. These findings demonstrate that reusability alone does not guarantee environmental benefit. Thus, usage frequency is the determining factor in whether reusable packaging delivers on its sustainability promise.

To examine how usage frequency shapes the sustainability performance of reusable packaging, this study compared the impacts of production, reuse, disposal, and recycling across seven objectives (Fig. 4). The impacts of each stage are presented as 100% stacked bars to clearly illustrate the main impact contribution of each objective at different usage amounts.

At one use, cup production and disposal dominate all seven objectives, contributing 75–95% of total environmental impact, indicating Design 16′s poor initial performance. As usage increases to 100 uses, a dramatic shift occurs: the reuse stage emerges as the primary contributor at 70–85% of total impact, while manufacturing's relative contribution shrinks as its burden is amortized across multiple uses. This reuse impact reflects accumulated burdens from washing (water, detergent, energy) and logistics. Beyond 200 uses, the structure stabilizes with manufacturing at 5–15% and reuse at 75–90%. Further usage increases yield diminishing environmental returns because operational impacts now define performance rather than manufacturing amortization.

Once usage exceeds 100 uses, manufacturing contributes only 10–25% of total impact, and by 200+ uses it drops to just 5–15%. Consequently, using recycled materials, bio-based plastics, or other “green” manufacturing inputs provides limited improvement to overall environmental performance. This shares similar findings with previous studies (Bradley and Corsini, 2023; Cottafava et al., 2024; Jerome and Ljunggren, 2025). Instead, design priorities should focus on maximizing cup durability and optimizing reuse processes. A durable cup made from conventional polypropylene that survives 300 uses with efficient cleaning protocols delivers far better environmental outcomes than a cup made from sustainable materials that breaks after 80 uses or requires intensive washing. This highlights the importance of operational efficiency, minimizing water, and energy consumption during washing, establishing efficient collection and logistics systems, and ensuring structural durability.

3.2. Pareto optimal solutions

This study identified 9 distinct Pareto-optimal solutions (Table 1). These solutions are based on combinations or the sole use of the 18 designs discussed in the previous section. The Pareto-optimal solutions can be categorized into two groups:

The first group consists of single-use packaging solutions, comprising Solutions 1, 2, and 3. Solution 1 employs pure PS plastic cups with a 100% disposal pathway, making it optimal only when cost minimization is the sole priority due to its high GWP and marine ecotoxicity. Conversely, Solution 2 utilizes PP plastic cups (89% recycling), incurring a 43% cost premium but achieving an 80% reduction in GWP alongside excellent human toxicity performance. This solution also exhibits negative eutrophication from recycling credits, though it shows the highest abiotic depletion. Solution 3 employs PS plastic cups with 89% recycling at 2077,997 NTD, balancing economic and climate concerns with moderate GWP.

The second group is characterized by reusable PP cup configurations (Solutions 4–9), all costing approximately 4,795,000 NTD. These solutions demonstrate that reusable PP cups provide optimal perfor-

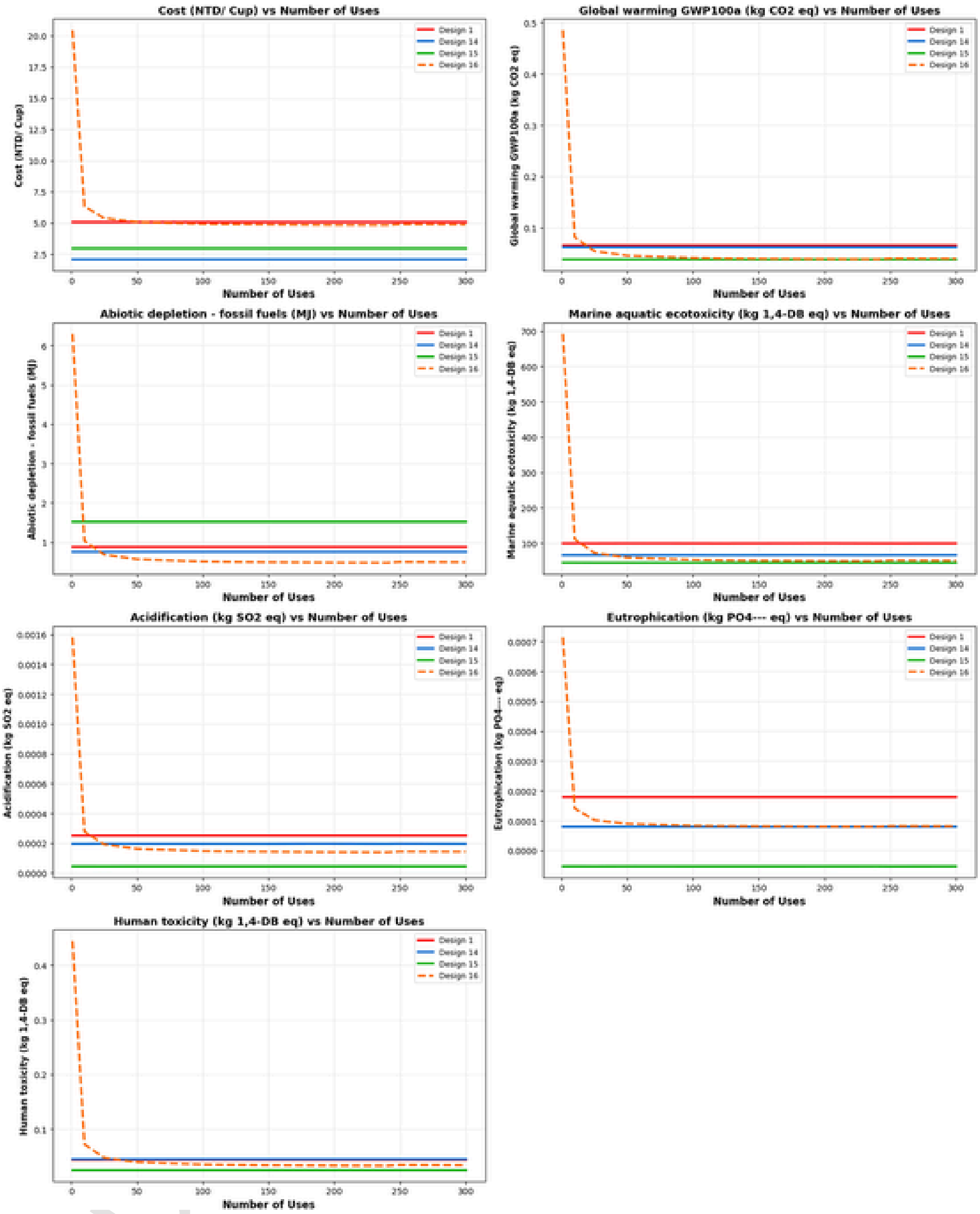

Fig. 3. Representative LCA results of bubble tea packaging design No 1, 14, 15, 18.
This figure presents a comprehensive comparison of four bubble tea packaging designs (Designs 1, 14, 15, and 16) across seven environmental impact categories and cost, all plotted against the number of uses. The charts report cost per cup, global warming potential, abiotic depletion of fossil fuels, marine aquatic ecotoxicity, acidification, eutrophication, and human toxicity.

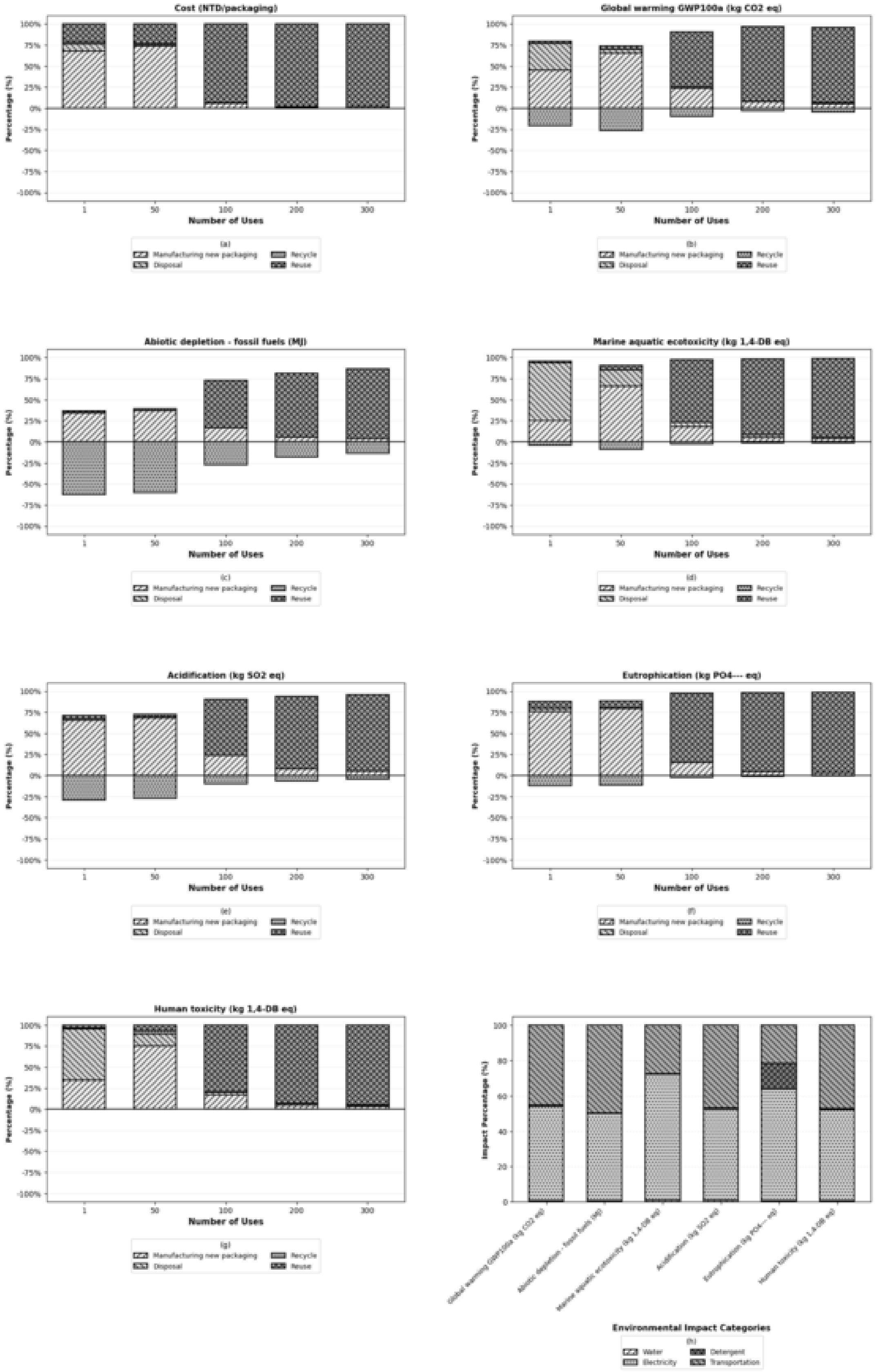

Fig. 4. LCA results of design No 15: reusable PP bubble tea packaging.

Fig. 4.—*continued*

This figure presents the LCA results of Design No 15, a reusable PP bubble tea packaging design, showing the relative contributions of different life cycle stages to cost and environmental impacts across varying numbers of uses (1, 50, 100, 200, and 300). The analysis covers seven dimensions: cost, global warming potential, abiotic depletion of fossil fuels, marine aquatic ecotoxicity, acidification, eutrophication, and human toxicity. Each stacked bar chart shows the percentage contribution from four life cycle stages: manufacturing new packaging (diagonal lines), disposal (dotted pattern), recycling (grid pattern), and reuse (cross-hatch pattern). The bottom-right panel (h) provides a detailed breakdown of the reuse process itself, displaying how different resources, water, electricity, detergent, and transportation, contribute to six environmental impact categories.

Table 1

Pareto-optimal solutions of sustainable bubble tea packaging design.

Optimal Solution	Design	Material	EoL treatment	Cost (NTD)	Global warming GWP100a (kg CO2 eq)	Abiotic depletion - fossil fuels (MJ)	Marine aquatic ecotoxicity (kg 1,4-DB eq)	Acidification (kg SO2 eq)	Eutrophication (kg PO4— eq)	Human toxicity (kg 1,4-DB eq)
1	Single use PS Plastic cup	Cup and Lid: PS	100% Disposal	2,061,221.5	192,310	47,790	2,281,690	111,323,220	83.24	404.19
2	Single use PP PLastic cup	Cup and Lid: PP	89% Recycle 11% Disposal	2,988,580.465	38,629.8	25,346.2	1,525,054.5	44,099,050	−53.0861	44.1887
3	Single use PS Plastic cup	Cup and Lid: PS	89% Recycle 11% Disposal	2,077,996.665	62,485.7	45,022.1	763,465.7	65,859,350	79.6088	191.4711
4	99.89% PP reusable cup	Cup and Lid: PP	89% Recycle 11% Disposal	4,795,336.831	38,437.68733	32,755.01295	469,830.1598	48,655,252.44	79.30973738	138.4497126
	0.10% HDPE reusable cup	Cup and Lid: HDPE	89% Recycle 11% Disposal							
	< 0.01% Single use PP plastic cup	Cup and Lid: PP	89% Recycle 11% Disposal							
5	100% PP reusable cup	Cup and Lid: PP	89% Recycle 11% Disposal	4,795,342.693	38,437.30272	32,755.0485	469,826.711	48,653,472.88	79.30826458	138.4484473
6	99.89% PP reusable cup	Cup and Lid: PP	89% Recycle 11% Disposal	4,793,415.02	38,436.92799	32,746.69656	470,939.8075	48,647,581.1	79.16713953	138.3469974
	0.11% Single use PP Plastic cup	Cup and Lid: PP	89% Recycle 11% Disposal							
7	99.89% PP reusable cup	Cup and Lid: PP	89% Recycle 11% Disposal	4,795,338.599	38,437.57936	32,754.92584	469,828.4735	48,655,035.25	79.30971482	138.4495343
	0.11% HDPE reusable cup	Cup and Lid: HDPE	89% Recycle 11% Disposal							
8	99.99% PP reusable cup	Cup and Lid: PP	89% Recycle 11% Disposal	4,795,155.785	38,437.16598	32,754.14761	469,930.4165	48,652,841.29	79.2947145	138.4383758
	0.01% Single use PP Plastic cup	Cup and Lid: PP	89% Recycle 11% Disposal							
9	99.99% PP reusable cup	Cup and Lid: PP	89% Recycle 11% Disposal	4,795,088.756	38,439.46418	32,755.99361	469,853.1019	48,654,890.62	79.30796437	138.4528144
	0.01% Single use PS Plastic cup	Cup and Lid: PS	88% Recycle 12% Disposal							

mance across diverse environmental objectives depending on priority emphasis. Solutions 4–9 are nearly pure reusable systems (99.89%–100% PP reusable cups) with minor variations in composition, yet each emerges as optimal for different objective combinations. This clustering of reusable solutions indicates that reusable PP cups inherently dominate the multi-objective solution space, within which specific configurations emerge as optimal, depending on the relative weighting of economic versus environmental objectives.

Notably, paper packaging designs (Category A) were not selected in any optimal solutions. This exclusion stems from the fact that paper packaging recycling processes, including pulping, de-inking, and reprocessing, cannot offset its production burdens. In contrast, plastic recycling provides substantial environmental credits by displacing virgin polymer production. Paper packaging also exhibits surprisingly high marine ecotoxicity due to chlorine-based bleaching agents used during production, with impacts comparable to plastic packaging alternatives. Additionally, paper packaging costs approximately twice as much as the most economical plastic options. These compounding disadvantages eliminate paper packaging from consideration despite its perceived sustainability benefits.

3.3. *Improving environmental performance of reusing process*

Based on previous results, the reuse process shows significant potential for improving reusable packaging sustainability. This section identifies the critical hotspots in the reusable packaging system. Fig. 4(h) presents a breakdown of environmental impacts attributable to water, electricity, detergent, and transportation. The LCA results reveal that electricity and transportation constitute the predominant contributors across most impact categories. Electricity consumption accounts for approximately 40–50% of impacts and transportation contributes an additional 35–45%. Notably, detergent use emerges as the dominant contributor to Eutrophication (approximately 15–20% of total impact), confirming the earlier observation regarding the trade-off between reusable packaging and nutrient loading. Water consumption, while necessary for washing operations, represents a relatively minor proportion (< 5%) of the environmental impacts in the reuse process stage, indicating that water use itself is not the primary environmental concern in reusable packaging systems. Nevertheless, in regions facing increasing water stress such as Taipei, volumetric water consumption from washing operations may warrant additional consideration beyond its relative contribution to standard LCA impact scores.

These findings highlight three operational priorities: transitioning to renewable energy sources for washing facilities, adopting energy-efficient equipment with heat recovery systems, and optimizing collection logistics through route planning and decentralized washing centers. Additionally, the use of phosphate-free, biodegradable detergents is essential to mitigate eutrophication impacts. Implementing these operational improvements could substantially reduce the environmental footprint of reusable packaging systems and enhance their competitiveness against optimized single-use alternatives.

3.4. *Analysis of multi-objective trade-offs and policy implications*

To reveal critical trade-offs between economic and environmental objectives in packaging selection, the correlation matrix provides insight into the factors driving optimal solutions and offers guidance for policy interventions (Fig. 5). The matrix demonstrates pronounced negative correlations between cost and most environmental indicators, except Eutrophication. These negative correlations indicate that more economical packaging options typically impose greater environmental burdens across multiple impact categories, highlighting the fundamental challenge of achieving both economic efficiency and environmental sustainability.

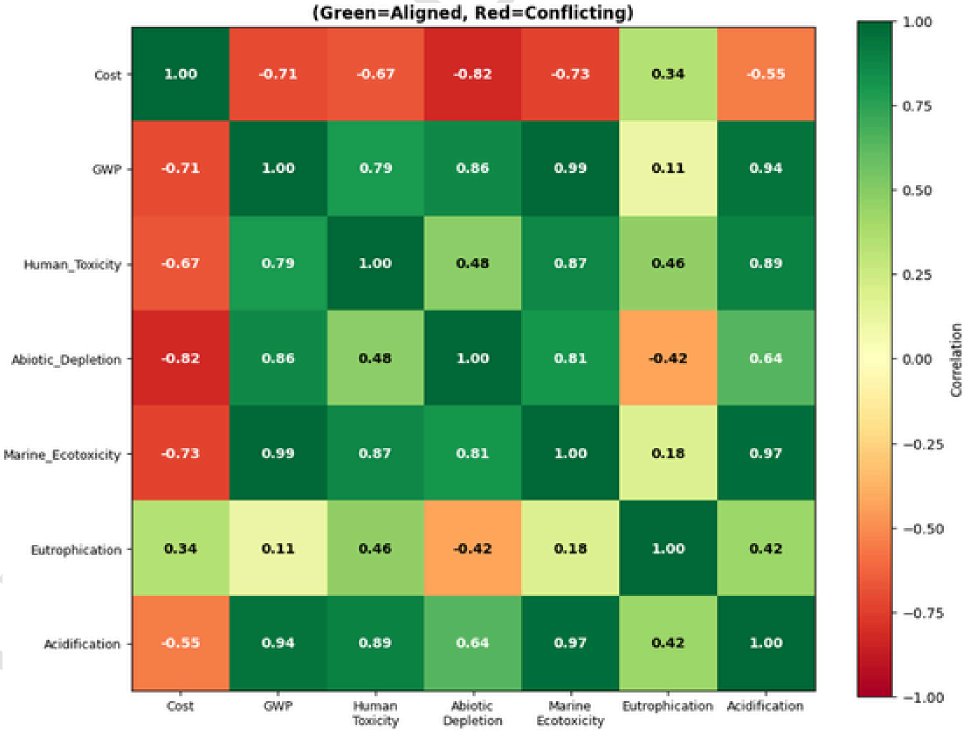

Fig. 5. Correlation matrix of 7 optimization objectives for sustainable bubble tea packaging design.
This figure displays an objective correlation matrix comparing cost and six environmental impact categories for bubble tea packaging designs. The matrix uses a color-coded heatmap where green indicates positive (aligned) correlations and red indicates negative (conflicting) correlations. The correlation values range from −1.00 to 1.00 and are displayed numerically and by color intensity.

In contrast, most environmental objectives demonstrate strong positive correlations with one another. Notably, GWP shows high alignment with Marine Ecotoxicity (0.99), Acidification (0.95), and Abiotic Depletion (0.85), suggesting that packaging solutions minimizing climate impacts tend to simultaneously reduce other environmental burdens. This synergy simplifies decision-making, as improvements in one environmental dimension often yield co-benefits across others.

This correlation structure provides valuable insights for policymakers designing interventions in the bubble tea packaging sector. The strong positive correlations among GWP, Marine Ecotoxicity, Acidification, and Abiotic Depletion suggest that these objectives can be effectively addressed through unified policy instruments. For instance, a policy instrument targeting GWP reduction would simultaneously incentivize improvements across marine ecotoxicity, acidification, and resource depletion, maximizing regulatory efficiency.

However, the consistent negative correlation between cost and environmental objectives presents a fundamental challenge: better environmental performance costs more. Economic incentives are therefore essential to make sustainable packaging financially competitive. Without policy intervention, market forces will consistently favor economically optimal but environmentally detrimental options. Potential policy mechanisms include environmental taxes on high-impact packaging materials to internalize externalities and level the economic playing field, or deposit-refund systems that encourage circular material flows.

The negative correlation between Eutrophication and Abiotic Depletion (−0.38) is particularly noteworthy, indicating potential trade-offs where reducing resource depletion may inadvertently increase nutrient loading. This divergent behavior suggests that the increasing selection of reusable packaging reduces the abiotic depletion relative to single-use plastic packaging but increase Eutrophication due to detergent use in reusing operations. This indicates that policies promoting reusable packaging must be accompanied by complementary measures, such as improved wastewater treatment standards, eco-friendly detergent regulations, and proper washing facility management.

3.5. Industrial feedback and model validation

3.5.1. Industry perspective on cost-environment trade-offs

The industry partners acknowledged that environmentally friendly solutions typically require higher investment under current market conditions. Their responses are consistent with the trade-off between cost and environmental objectives shown in Fig. 5. While ranking the seven environmental and economic indicators examined in the study, the industry partners ranked cost as the primary consideration (in the absence of specific regulations or subsidies), followed by global warming potential (driven by government expectations), and human toxicity (due to direct consumer impact). This ordering reflects the reality that economic viability remains the fundamental prerequisite for system adoption. Current market conditions show that high costs deter merchant participation, limited merchant networks reduce consumer convenience and adoption, and low consumer uptake undermines the economies of scale needed to lower costs. The industry partners also suggested that policy approaches, such as environmental taxes and deposit-refund systems, are needed to support reusable cup systems.

The industry partners' responses largely support the model's findings regarding the environmental and economic performance of different cup systems. They agreed that the lowest-cost option would exhibit the worst environmental performance, noting that among plastic materials, PS is inherently more environmentally harmful. The mixed-design compositions in Solutions 4–9, where PP reusable cups dominate with a residual fraction of single-use designs, were regarded by industry partners as practically realistic. In their business experience in Taiwan, no single design can realistically achieve 100% market penetration unless specific designs or materials are banned by policy. They therefore emphasized that policy and promotion should concentrate on one primary design rather than simultaneously targeting multiple alternatives. The dominance of PP reusable cups across optimal solutions thus signals strong sustainability potential, while the residual single-use fraction reflects a realistic market transition, one where even incomplete dominance of reusable systems would represent a substantial improvement in overall packaging sustainability.

3.5.2. Practical constraints on reuse cycle assumptions

However, the industry partners expressed reservations about potential overestimation in the model's assessment of reusable cup performance. While confirming that PP reusable cups can technically achieve 120 usage cycles under normal conditions (Fig. 3), the industry partners emphasized that optimal usage frequencies are often hindered by premature cup retirement in practice. Primary reasons for premature cup retirement are appearance degradation during circulation (often linked with hygiene concerns), cup loss, and physical damage. Notably, the industry partner emphasized that even when cups maintain structural integrity for 200–300 uses, visible wear from repeated washing creates consumer hesitation, effectively shortening the functional lifespan below technical capacity. This observation highlights how consumer perception, rather than material failure, often dictates the practical lifecycle of reusable cups, implying that aesthetic durability may be as critical as functional durability in system design. Therefore, they suggested incorporating a diminishing returns concept into our model to more accurately reflect actual usage patterns over time (Supplementary Material S1, Tables S1–S5). Furthermore, the biodegradable single-use packaging company argued that the lower usage times would provide an opportunity for biodegradable single-use cups to increase their market share. However, the sensitivity analysis suggests that even under reduced usage assumptions, reusable PP solutions remain competitive in most scenarios.

3.5.3. Strategies for enhancing reusable packaging

The industry partners agreed with the model results in Fig. 4 that electricity and transportation are major hotspots in the reusable system. In practice, they paid more attention to transportation and cleaning efficiency instead. An industry partner from a reusable packaging company (Company B) strongly favored decentralized washing systems (onsite at retail locations) over centralized facilities due to prohibitively high transportation costs and spatial constraints in Taipei's urban center. For improving cleaning efficiency within existing or future systems, the industry partners prioritized coating technology to reduce cleaning requirements, followed by structural design modifications, with material selection ranked lowest. Company B recommended developing specialized cleaning equipment and protocols specifically designed for beverage cups to eliminate unnecessary cleaning steps. Despite the availability of alternative sanitation technologies (UV sterilization, ozone treatment), Company B preferred traditional detergent-based cleaning because of consumer familiarity and acceptance. This preference reflects the importance of consumer trust in driving system adoption.

4. Conclusion

This paper contributes to LCA methodologies by introducing a demand-driven perspective and integrating it with multi-objective optimization. By addressing the limitations inherent in traditional supply-oriented LCA studies, this study shifts the focus toward demand-side considerations, enabling more context-specific insights. The multi-objective optimization model effectively highlights key trade-offs and identifies optimal packaging design solutions balancing economic viability with substantial reductions in environmental impacts.

Key findings reveal that reusable PP packaging appears in the most Pareto-optimal solutions, demonstrating significant potential for implementing reusable systems as the primary approach to enhancing bubble tea packaging sustainability. However, usage frequency emerges as the critical success factor: reusable PP cups require a minimum threshold of 120 uses to justify their manufacturing burden, with optimal performance beyond 300 uses. Below this threshold, reusable systems represent net environmental harm compared to single-use alternatives.

This usage-dependent performance reveals critical improvement opportunities in the reusing process. Once usage exceeds 100 uses, the environmental impacts are primarily driven by the reuse process, particularly electricity consumption and transportation. These findings shift design priorities from sustainable material selection toward maximizing cup durability, optimizing collection logistics, transitioning to renewable energy for washing facilities, and implementing phosphate-free detergents to mitigate eutrophication impacts.

Industry feedback provides crucial real-world perspectives on optimization findings. The industry partners confirmed the model's core findings on the cost-environment trade-off and PP reusable cup dominance, but identified premature cup retirement driven by appearance degradation and consumer perception as a key implementation barrier, highlighting that aesthetic durability may be as critical as functional durability in system design. They further prioritized decentralized washing systems and coating technology to reduce cleaning requirements as the most promising strategies for improving the operational efficiency of reusable packaging systems.

Several limitations of the current model should be acknowledged. First, LCA coefficients sourced from Ecoinvent 3.9.1 carry inherent measurement uncertainty and regional approximation error. Second, consumer demand is modeled as a fixed aggregate parameter, and behavioral factors, such as consumer return compliance, usage frequency, and perception-driven retirement decisions, are not endogenously captured. Finally, the model relies on fixed parameters for reuse cycle limits and recycling rates, which limits the model's ability to capture dynamic real-world factors.

Future research should pursue two directions: First, integrating behavioral and preference-based factors into the optimization framework to better capture how consumer perceptions and usage behaviors influence real-world adoption. Second, developing robust social LCA metrics to account for labor conditions, community well-being, and other societal impacts currently omitted due to the lack of standardized methodologies and reliable data.

Data availability

Life Cycle Inventory data for bubble tea packaging design alternatives (Mendeley Data).

CRediT authorship contribution statement

Yan-Ruei Huang: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Yu-Kai Liao:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Ching-Pin Tung:** Writing – review & editing, Supervision, Conceptualization. **Wei-Chun Chuang:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that has been used is confidential.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2026.108962.

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