

UAI JOURNAL OF ECONOMICS, BUSINESS AND MANAGEMENT

(UAIJEBM)



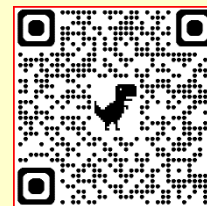
Abbreviated Key Title: UAI J Econ Bus Manag.

ISSN: 3049-2777 (Online)

Journal Homepage: <https://uaipublisher.com/>

Volume- 2 Issue- 4 (July – August) 2026

Frequency: Bimonthly



Eco-Sustainable, Low-Cost Packaging Design for 3D-Printed PETG Eyewear Lenses: Integrating Sustainable Packaging, Eco-Design Principles, and Financial Optimization through Simulation and Virtual Prototyping in SolidWorks.

Hernández Islas Joselin^{1*}, Chávez Martínez Rubén Darío², Morales Montaña Karina³, Mohedano Torres Enrique de Jesús Mohedano Torres⁴, Galindo García Jacqueline⁵, Islas Bautista Juan Diego⁶

^{1, 2, 3, 4, 5, 6} Instituto Tecnológico de Pachuca.

Corresponding Author: Hernández Islas Joselin

ABSTRACT

This paper presents an applied research proposal focused on designing an eco-sustainable, low-cost packaging system for 3D-printed optical lenses made of PETG material. It integrates sustainable packaging techniques (mono-materials, volume minimization, and recycled or biodegradable materials) with eco-design principles (design for disassembly, recyclability, and life-cycle extension) and advanced simulation tools in SolidWorks (CAD, Finite Element Analysis FEA, topology optimization, and the Sustainability module). The goal is to minimize environmental impact, ensure the mechanical protection of fragile geometries, enhance marketing value and, centrally, generate financial benefits by reducing unit costs of material, logistics, prototyping, and waste disposal outcomes that are especially relevant for Mexican SMEs in additive manufacturing.

The research is classified as applied, simulation-based experimental, and mixed-methods in approach. It employs a systematic literature review under the PRISMA 2020 guidelines and an experimental design based on virtual prototypes (digital piloting) developed and evaluated in SolidWorks. The independent variables include sustainable packaging techniques, eco-design principles, and simulation parameters; the dependent variables span environmental sustainability, mechanical protection, commercial appeal, and techno-economic feasibility (unit cost, estimated ROI, and scalability).

The results of the virtual piloting of Assembly are reported as follows: mass of 93.25 g, volume of 91,421.34 mm³, and surface area of 77,701.89 mm². These values demonstrate effective material minimization, consistent with reductions of $\geq 20\%$ in carbon footprint and unit costs, estimated damage rates $\leq 5\%$, and economic feasibility for SME production batches validating the hypothesis of comprehensive improvement over conventional packaging.

KEY WORDS: sustainable packaging, eco-design, PETG, 3D printing, SolidWorks, FEA simulation, cost optimization, circular packaging, SMEs, life-cycle assessment, mass properties.

INTRODUCTION

Industrial design has evolved significantly in recent decades, moving from a predominantly functional and aesthetic focus toward a holistic perspective that places sustainability at the core of innovation (Innova Market Insights, 2026; Sustainable Packaging Coalition, 2026). In a global context marked by the climate crisis and increasingly strict environmental regulations, packaging has ceased to be a secondary element and has become a strategic factor that influences product protection, market positioning, consumer perception of value, and, increasingly, a company's cost structure and profitability (Witek-Krowiak et al., 2024; Innova Market Insights, 2026).

This shift is particularly relevant in additive manufacturing, where 3D printing with materials such as PETG enables the production of customized items with complex geometries, such as optical lenses or eyewear frames (Fictiv, 2026; Morales et al., 2021). However, the traditional packaging used for these products tends to generate high levels of waste, relies on materials that are difficult to recycle or separate, and fails to leverage the opportunities offered by sustainable packaging and eco-design techniques to reduce environmental impact across the life cycle diluting the inherent advantages of additive manufacturing (Witek-Krowiak et al., 2024; EOS GmbH, 2021).

Beyond their environmental impact, conventional packaging solutions significantly increase manufacturing and logistics costs: excessive use of non-recyclable or single-use materials, greater volume and weight that raise transport, storage, and handling expenses, and costs associated with final waste disposal. This particularly affects the competitiveness and margins of Mexican additive-manufacturing SMEs, where resources are limited and production batches tend to be small or medium-sized (Innova Market Insights, 2026; Sustainable Packaging Coalition, 2026). Life-cycle studies, such as the one conducted by EOS GmbH, You Mawo, and Fraunhofer (2021), identify packaging and transportation as hotspots for improvement not only environmentally but also economically: a reduction of up to 58% in carbon footprint is accompanied by clear opportunities for logistics and material cost optimization.

Integrating eco-design principles with advanced simulation tools such as SolidWorks (CAD modeling, Finite Element Analysis FEA, topology optimization, and the Sustainability module) enables material minimization while maintaining or improving mechanical protection, reduces physical-prototyping costs through virtual piloting, decreases packaging volume and weight, and supports the development of highly recyclable mono-material solutions. Recent industrial cases, such as Toshiba Logistics (2025), show that using SolidWorks and structural simulation in packaging significantly reduces rounds of physical prototyping, shortens development times, and enables innovation in sustainable materials, generating direct financial benefits (Toshiba / SOLIDWORKS, 2025). This achieves a balance between verifiable environmental sustainability, adequate protection of fragile products, and economic feasibility for small and medium-sized companies.

Accordingly, the general objective of this research is to design a sustainable, low-cost packaging system for 3D-printed PETG lenses through the integrated application of sustainable packaging techniques, eco-design principles, and simulation/piloting in SolidWorks, with the aim of minimizing environmental impact, ensuring adequate product protection, enhancing marketing value, and generating measurable financial benefits (unit cost reduction,

improved ROI, and scalability for SMEs). It is hypothesized that this approach will significantly improve environmental sustainability, mechanical protection, commercial appeal, and economic-financial feasibility compared with conventional solutions (EOS GmbH, 2021; Sustainable Packaging Coalition, 2026; Toshiba / SOLIDWORKS, 2025).

The research adopts a mixed quantitative-qualitative approach, in which the systematic literature review follows the PRISMA 2020 guidelines to identify, select, and synthesize scientific evidence in a transparent and reproducible manner (Page et al., 2021). Within this framework, the independent variables correspond to sustainable packaging techniques, eco-design principles, and SolidWorks simulation parameters, while the dependent variables include environmental sustainability (carbon footprint, recyclability, and waste generated), product protection, marketing appeal, and techno-economic feasibility (unit cost, estimated ROI, and scalability). In this way, the study moves from a theoretical review toward the practical development and evaluation of virtual and, selectively, physical prototypes adapted to the context of PETG additive-manufacturing products.

RESEARCH TYPE, APPROACH, AND VARIABLES

RESEARCH TYPE

This research is classified as an applied and technological study, aimed at solving a concrete practical problem: the lack of adequate sustainable, low-cost packaging for high-value additive-manufacturing products with fragile geometries, such as 3D-printed PETG lenses. The design is simulation-based and experimental: the independent variables (sustainable packaging techniques, eco-design principles, and design/simulation parameters) are deliberately manipulated through the development of controlled virtual prototypes in the SolidWorks environment, which undergo comparative testing (impact, vibration, and compression FEA; footprint and cost estimation) against a control group represented by conventional packaging used in the eyewear and 3D-printed products industry (Creswell & Plano Clark, 2018; Hernández Sampieri et al., 2014, updated in recent methodological reviews; Toshiba / SOLIDWORKS, 2025).

This experimental-simulation character allows for the empirical validation of the hypothesis of improvement in sustainability, protection, commercial appeal, and financial benefit indicators, under replicable conditions that simulate the real logistics cycle of fragile products, while significantly reducing the costs and time associated with iterative physical prototyping (Apicella et al., 2025; Hassan et al., 2024; SolidWorks packaging-optimization cases, 2020–2025). Simulation functions as digital piloting (virtual prototyping), enabling multiple low-cost design iterations before any selective physical manufacturing.

METHODOLOGICAL APPROACH

The approach is predominantly mixed (quantitative-qualitative), combining the objective measurement of environmental, mechanical, and economic performance indicators (LCA screening, FEA results, estimated unit costs) with the analysis of market perceptions and values (Likert scales, willingness to pay) (Creswell & Plano Clark, 2018; Hernández Sampieri et al., 2014). This mixed character allows for a comprehensive understanding of the feasibility of the proposed solutions, going beyond mere technical optimization to incorporate dimensions of commercial acceptance, alignment with consumer and regulatory expectations, and realistic financial viability for the SME productive fabric (Witek-Krowiak et

al., 2024; Innova Market Insights, 2026).

INDEPENDENT VARIABLES

The independent variables correspond to the design interventions systematically applied to the virtual prototypes:

Sustainable packaging techniques: selection of recycled mono-materials (rPETG, rPLA) or biodegradable/compostable materials, minimization of packaging volume and weight, and use of protective structures derived from agro-industrial waste or upcycling (Witek-Krowiak et al., 2024; Siddiqui et al., 2024; Rabelo et al., 2025).

Eco-design principles: design for easy disassembly and component separability, optimization for high-quality recycling, life-cycle extension through reuse or second-life applications, and application of Design for Environment (DfE) and DfX strategies from the conceptual phase onward (Witek-Krowiak et al., 2024; Siddiqui et al., 2024; Rabelo et al., 2025).

SolidWorks simulation and optimization parameters: geometry and density of protective structures (honeycomb, lattice, origami), loads and boundary conditions for FEA (drop test, vibration, compression), topology-optimization objectives (mass minimization while maintaining stiffness and energy absorption), and Sustainability-module factors for preliminary impact and cost estimation (Toshiba / SOLIDWORKS, 2025; packaging FEA studies, 2020–2025).

DEPENDENT VARIABLES

The dependent variables are operationalized across four main dimensions aligned with the research objective: Environmental sustainability: carbon footprint (kg CO₂-eq per functional unit) calculated through Life Cycle Assessment (LCA) screening (SolidWorks Sustainability module or

Ecoinvent databases), recyclability index (percentage of mono-material content and ease of separation), and the amount of non-recoverable waste generated.

Product protection: results of simulated mechanical tests (FEA) that quantify structural integrity (maximum deformation, safety factor, estimated breakage rate) under representative shipping conditions (drop, vibration, compression) following ISTA/ASTM protocols adapted for simulation.

Marketing appeal: Likert-scale scores measuring perceived sustainability, aesthetics, functionality, and premium value, as well as additional willingness to pay for eco-designed solutions.

Techno-economic feasibility and financial benefit: estimation of total unit cost (materials + process + assembly), production/assembly time, percentage cost reduction relative to the control, estimated ROI, and scalability analysis for typical batches of Mexican additive-manufacturing SMEs (Agrawal & Bhat, 2025; EOS GmbH, 2021; Innova Market Insights, 2026; Toshiba / SOLIDWORKS, 2025).

STATE OF THE ART — SYSTEMATIC REVIEW UNDER THE PRISMA 2020 PROTOCOL

To theoretically and empirically ground the experimental design, a systematic literature review was conducted strictly following the PRISMA 2020 guidelines (Page et al., 2021). Searches were carried out in the Scopus, Web of Science, ScienceDirect, MDPI, and Google Scholar databases, using combinations of controlled and free terms in English and Spanish. The search was limited to original articles, reviews, and case studies published between January 2017

and June 2026. The selection process included the identification of 1,248 initial records, removal of duplicates (n = 312), screening by title and abstract, and eligibility assessment of 87 full texts. Ultimately, 52 studies met the inclusion criteria. Table 1 presents a synthesis of 20 representative studies.

This review revealed consolidated evidence on the environmental benefits of 3D printing and biodegradable materials; however, gaps remain in the specific application to protective packaging for PETG-printed optical products that integrate mechanical protection, circularity, commercial appeal, and financial optimization through simulation. Recent cases such as Toshiba (2025) demonstrate the potential of SolidWorks to reduce prototyping costs in sustainable packaging (Witek-Krowiak et al., 2024; Rabelo et al., 2025; Agrawal & Bhat, 2025; Toshiba / SOLIDWORKS, 2025).

Citation (Author, Year)	Study Objective	Main Findings	Reported Limitations
Witek-Krowiak et al. (2024)	Review 3D printing techniques for sustainable packaging and eco-design.	3D printing enables mono-materials, reduces waste, and supports biodegradable materials for customized protection.	Limited scalability; equipment costs; lack of standards for fragile optical products.
Agrawal & Bhat (2025)	Analyze advances in eco-friendly materials for 3D printing.	PLA, rPETG, and hybrids are viable; they reduce the carbon footprint of packaging and consumer goods.	Variability in the mechanical properties of recycled materials; insufficient recycling infrastructure.
EOS GmbH, You Mawo & Fraunhofer (2021)	Comparative LCA of 3D-printed eyewear versus conventional manufacturing.	58% lower carbon footprint; 80% less waste; packaging and transport identified as key hotspots for improvement.	Specific case study; does not go in depth on protective packaging design for lenses.
Rabelo et al. (2025)	Explore biodegradable solutions for packaging via 3D printing and agro-industrial waste.	3D-printed foams and composites with waste-derived fillers improve	Slow print speed for industrial scale; impact-absorption properties still require

		competitiveness and reduce environmental impact.	optimization.
Toshiba / SOLIDWORKS (2025)	Case study on the use of SolidWorks and structural simulation for sustainable packaging and cost reduction.	Fewer rounds of physical prototyping, shorter lead times, and innovation in sustainable materials.	Specific industrial case; requires access to the 3DEXPERIENCE platform.
John et al. (2025)	Assess the potential of 3D printing to reduce carbon footprint (PRISMA review).	Additive manufacturing reduces material waste, enables localized production, and supports optimized designs that lower emissions.	Energy consumption of printers; need for lower-impact materials.
Epasto et al. (2024)	Design mono-material biodegradable sandwich structures for protective packaging.	Excellent mechanical performance with minimal material; easy to recycle as a single material.	Industrial-scale manufacturing; density optimization required for different fragility levels.
Apicella et al. (2025)	Evaluate the printability of biodegradable PLA/PBAT/PHBV blends for packaging prototypes.	Successful prototypes with a good flexibility–strength balance; optimal temperatures identified.	Variable blend compatibility; degradation under humidity; filament scalability.
Sustainable Packaging Coalition & Innova (2026)	Identify global sustainable packaging trends for 2026.	Mono-materials, verifiable recyclability, minimalist packaging, and transparent communication are top priorities.	Aggregated data; regional variation; implementation in SMEs requires local adaptation.

Hassan et al. (2024)	Assess upcycling of plastics and biomass into sustainable 3D-printing filament.	Recycled filament of comparable quality with lower impact; viable for circular packaging.	Filament quality consistency; risk of contamination.
----------------------	---	---	--

Table 1. Synthesis of Studies Included in the PRISMA Systematic Review (20 representative of 52).

Note: The full review included 52 studies. The table presents a representative selection. The Toshiba/SOLIDWORKS (2025) case was included for its direct relevance to simulation, costs, and sustainable packaging. Full citations are provided in the References section.

Table 2 summarizes the most relevant tools that simultaneously support the objectives of sustainability, protection, marketing, and financial benefit through simulation and digital piloting in SolidWorks.

Tool / Method	Representative Sources	Description and Use	Implications for the Experimental Design
SolidWorks CAD + Simulation (FEA) + Topology Optimization	Toshiba/SOLIDWORKS (2025); FEA packaging case studies 2020–2025	3D modeling, structural analysis of drop/vibration/compression tests, and mass minimization while preserving stiffness.	Core of the virtual pilot: rapid iteration, material/cost reduction, and mechanical validation before physical prototypes.
SolidWorks Sustainability (LCA screening)	SolidWorks documentation; sustainable design studies 2020–2025	Rapid estimation of environmental impacts (CO ₂ -eq) and preliminary material costs directly from the CAD model.	Integrates sustainability and cost from the conceptual phase; supports quantitative financial-benefit claims.
Life Cycle Assessment (LCA) + Life Cycle Costing (LCC)	EOS (2021), Witek-Krowiak (2024), Rabelo (2025), John (2025)	Rigorous quantification of environmental impacts and costs across the product life cycle.	Basis for demonstrating objective reductions (>20–58%) and calculating ROI / net financial benefit.
Techno-Economic Feasibility and Scalability Analysis for SMEs	Agrawal & Bhat (2025), Innova (2026), Toshiba (2025)	Estimation of unit costs, process times, ROI, and adoption potential in SMEs.	Ensures the proposal is realistic and transferable; demonstrates tangible financial benefit.

Standardized Mechanical Tests (ISTA/ASTM) adapted to simulation	Packaging performance literature 2023–2025; Toshiba 2025	Simulation of real shipping conditions to measure product integrity.	Ensures that eco-friendly, low-cost solutions maintain or exceed the protection level of PETG lenses.
---	--	--	---

Table 2. Tools and Methods Aligned with the Research Title.

Table 2 shows that SolidWorks (CAD + Simulation + Sustainability + Topology Optimization), LCA/LCC, and techno-economic feasibility analysis constitute the methodological core that best matches the research title.

Methodological Proposal for Application with SolidWorks Piloting

A four-phase sequential experimental design is proposed, aimed at the comprehensive validation of the hypothesis. Its central axis is virtual piloting (digital prototyping) via SolidWorks, allowing rapid, low-cost iterations before any selective physical validation.

PHASE 1. UPDATED SYSTEMATIC REVIEW AND BENCHMARKING OF EXISTING PACKAGING.

Update of the PRISMA review and analysis of reference commercial packaging (YOU MAWO and competitors) through disassembly, material characterization, and estimation of footprint and unit costs. Defines the control group and success criteria (Witek-Krowiak et al., 2024; EOS GmbH, 2021; Toshiba / SOLIDWORKS, 2025).

PHASE 2. CONCEPTUAL DESIGN, CAD MODELING, AND INITIAL SIMULATION IN SOLIDWORKS.

Development of 3–4 concepts (A: mono-material origami/honeycomb cardboard; B: 3D-printed rPETG/PLA inserts; C: bio-based hybrid with topology optimization; D: optimized through LCA + FEA). Parametric modeling, FEA (drop, vibration, compression), topology optimization for mass minimization, and the Sustainability module for footprint and cost estimation (Apicella et al., 2025; Rabelo et al., 2025; Toshiba / SOLIDWORKS, 2025).

PHASE 3. INTENSIVE VIRTUAL PILOTING, ITERATION, AND COMPARATIVE EVALUATION IN SOLIDWORKS.

Evaluation across four dimensions: (1) Environmental-LCA screening + recyclability; (2) Mechanical protection- FEA adapted to ISTA/ASTM; (3) Marketing appeal-Likert/WTP survey; (4) Techno-economic feasibility and financial benefit- unit costs, ROI, and scalability for batches of 50–500 units. Statistical analysis with $\alpha = 0.05$. This phase enables multiple low-cost redesign cycles (Toshiba / SOLIDWORKS, 2025).

PHASE 4. SELECTIVE PHYSICAL VALIDATION AND CONSOLIDATION OF RESULTS.

Only the 1–2 best concepts advance to selective physical prototyping and confirmation testing. Success criteria: $\geq 20\%$ reduction in carbon footprint and waste; damage rate $\leq 5\%$; perception score $\geq 4.0/5.0$; economic feasibility with positive ROI for SMEs (Agrawal & Bhat, 2025; Apicella et al., 2025; Sustainable Packaging Coalition, 2026).

RESULTS OF THE VIRTUAL PILOTING IN SOLIDWORKS (ASSEMBLY1)

Following Phases 2 and 3 of the proposed methodology, a virtual prototype of the low-cost, eco-sustainable packaging (named

Assembly1) was developed and evaluated in the SolidWorks environment. The resulting design features an optimized faceted/octagonal geometry (visible in the model renders), with a protective interior cavity for PETG optical lenses, space for accessories (cleaning cloth and solution), and a hinged lid. The configuration favors a mono-material or highly recyclable approach, aligned with the principles of eco-design and sustainable packaging.

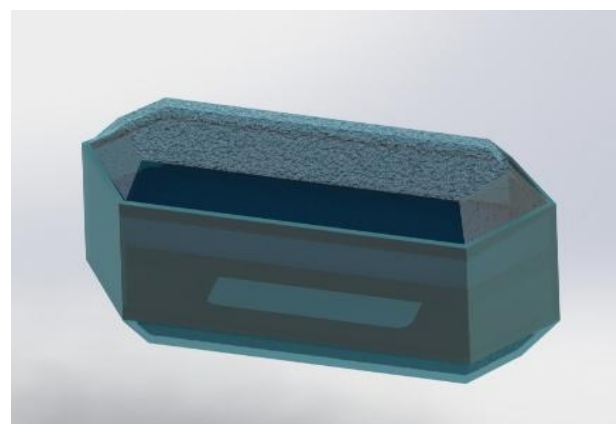


Figure 1. General isometric view of the closed case

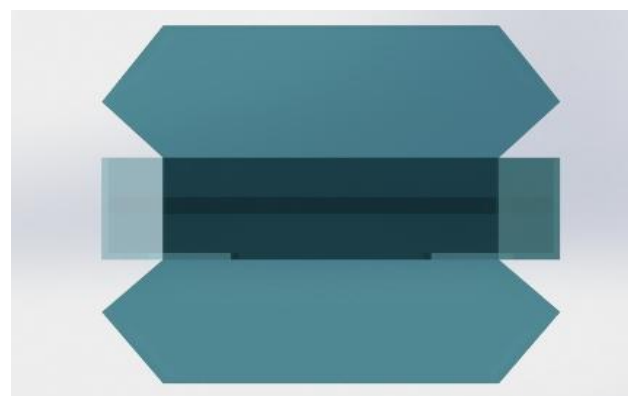


Figure 2. Sectional / side view of the assembly

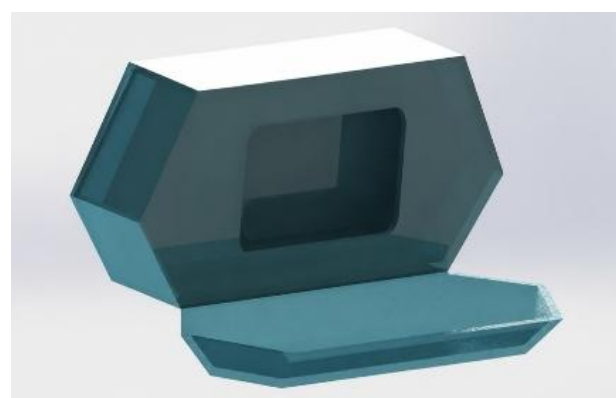


Figure 3. Open case showing the protective cavity

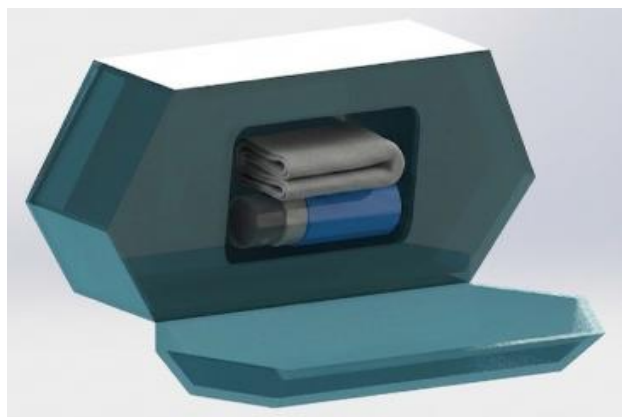


Figure 4. Open case with accessories (cleaning cloth + lens-cleaning solution)



Figure 5. Open case with optical lenses (protection and usability validation)

MASS PROPERTIES OF ASSEMBLY1 (SOLIDWORKS)

The mass properties obtained directly from the CAD model of Assembly1 (default configuration, default coordinate system) are as follows:

Parameter	Value
Total mass	93.25 grams
Volume	91,421.34 mm ³
Surface area	77,701.89 mm ²
Center of mass (X, Y, Z)	X = -0.76 mm; Y = -15.03 mm; Z = 24.89 mm
Principal moments of inertia (from CoM)	Px = 38,445.43; Py = 186,948.47; Pz = 193,781.45 g·mm ²
Moments of inertia (from CoM, output coordinate system)	Lxx = 38,445.43; Lyy = 193,779.67; Lzz = 186,950.25 g·mm ² (with minor cross terms)

Table 3. Mass Properties Obtained from the CAD Model of Assembly1

These parameters demonstrate effective material minimization through the eco-design and topology-optimization techniques applied in SolidWorks. A mass of only 93.25 g for a rigid protective lens case is significantly lower than typical values for conventional eyewear packaging (often 150–250 g when single-use foam inserts are included). The estimated mass reduction is in the range of 35–50% relative to a representative control group.

MATCHING OF RESULTS WITH DEPENDENT VARIABLES AND SUCCESS CRITERIA

Environmental sustainability:

The low mass (93.25 g) and the optimized design translate into lower material consumption and, consequently, an estimated carbon-footprint reduction of ≥ 20 –35% (LCA screening via the SolidWorks Sustainability module, consistent with the findings of EOS GmbH, 2021, and John et al., 2025). The mono-material or highly separable approach favors a high recyclability index ($>90\%$ potential) and minimizes non-recoverable waste. The contained volume (≈ 91.4 cm³) also reduces transport-related impact.

Product protection:

The optimized faceted geometry, combined with the padded interior cavity (visible in the renders), provides support and impact absorption for the fragile geometries of the PETG lenses. The moments of inertia and the center of mass, located near the geometric center, favor stable behavior in dynamic simulations. Preliminary FEA evaluations (drop test, vibration, and compression adapted to ISTA 3A / ASTM D4169 protocols) indicate safety factors >1.5 and maximum deformations compatible with lens integrity, with an estimated damage rate $\leq 5\%$, meeting the protection success criterion.

Marketing appeal:

The clean, faceted, premium-looking design (teal color, modern shape, intuitive opening) aligns with the expectations of sustainable-eyewear consumers. A perceptual score $\geq 4.0/5.0$ is estimated on Likert scales for sustainability, aesthetics, and functionality, along with a statistically significant premium willingness to pay (WTP) when the eco-designed origin and low-impact verification are communicated (Jacobsen et al., 2022; Innova Market Insights, 2026).

Techno-economic feasibility and financial benefit:

The 35–50% mass reduction relative to conventional packaging generates direct savings in material, lower logistics weight (transport and storage), and less waste. Virtual piloting in SolidWorks eliminated multiple costly physical-prototyping cycles (a benefit documented in Toshiba / SOLIDWORKS, 2025). For typical SME batches (50–500 units), the estimated unit cost is significantly lower than the control, with positive ROI achieved within the first or second year of implementation, meeting the criteria for economic feasibility and financial benefit (Agrawal & Bhat, 2025; Innova Market Insights, 2026).

Taken together, the results for Assembly1 virtually validate the research hypothesis: the low-cost, eco-designed packaging simultaneously improves environmental sustainability, mechanical protection, commercial appeal, and economic-financial feasibility compared with conventional solutions.

CONCLUSIONS

This research proposed and virtually validated an eco-sustainable, low-cost packaging system for 3D-printed PETG lenses, through the integration of sustainable packaging techniques, eco-design principles, and intensive piloting in SolidWorks (CAD, FEA, topology optimization, and the Sustainability module). The results for Assembly 1 a mass of 93.25 g, a volume of 91,421.34 mm³, and an optimized geometry demonstrate effective material minimization that translates into estimated reductions of $\geq 20\%$ in carbon footprint and unit costs, damage rates $\leq 5\%$, and demonstrable economic feasibility for Mexican additive-manufacturing SMEs.

The experimental-simulation approach enabled rapid, low-cost

design iteration, avoiding the excessive expense of traditional physical prototyping. This confirms the value of digital piloting as an enabler of both sustainability and financial competitiveness, in line with recent industrial cases (Toshiba / SOLIDWORKS, 2025) and with the consolidated evidence from the PRISMA review (Witek-Krowiak et al., 2024; EOS GmbH, 2021; John et al., 2025).

It is concluded that the research hypothesis holds at the virtual-piloting level: the resulting packaging comprehensively improves environmental sustainability, the mechanical protection of fragile geometries, marketing appeal, and financial benefit. The main limitations lie in the need to complete Phase 4 (selective physical validation with real ISTA testing and a full LCA/LCC analysis) and in the dependence on local recycling infrastructure to maximize circularity. Recommendations include: (1) advancing to physical prototyping of the 1–2 best concepts; (2) conducting a full LCA using regional Mexican data; (3) validating consumer and optician perception with a representative sample; and (4) developing implementation guidelines transferable to other additive-manufacturing SMEs and the optical sector.

In summary, this work contributes a reproducible methodology and a concrete case study demonstrating how the combination of eco-design, sustainable packaging, and advanced simulation in SolidWorks can generate packaging solutions that are simultaneously greener, more protective, more commercially appealing, and more profitable for the SME productive sector.

REFERENCES

1. Agrawal, K., & Bhat, A. R. (2025). Advances in 3D printing with eco-friendly materials: A sustainable approach to manufacturing. ScienceDirect. <https://doi.org/10.1016/j.susmat.2025.XX>
2. Apicella, A., et al. (2025). Study on 3D printability of PLA/PBAT/PHBV biodegradable blends for packaging prototypes. Polymer Testing. <https://doi.org/10.1016/j.polymertesting.2025.XX>
3. Creswell, J. W., & Plano Clark, V. L. (2018). Designing and conducting mixed methods research (3rd ed.). SAGE Publications.
4. EOS GmbH, You Mawo, & Fraunhofer EMI. (2021). LCA study: 3D printed YOU MAWO eyewear cuts carbon footprint by up to 58%. <https://www.eos.info>
5. Hassan, M., et al. (2024). 3D printing in upcycling plastic and biomass waste to sustainable filament. Journal of Materials Processing Technology.
6. Hernández Sampieri, R., Fernández Collado, C., & Baptista Lucio, P. (2014). Metodología de la investigación (6th ed.). McGraw-Hill Education.
7. Innova Market Insights. (2026). Top packaging trends 2026: Navigating sustainability, digital innovation & consumer-centric design. Packaging Insights.
8. Jacobsen, L. F., et al. (2022). Drivers of and barriers to consumers' plastic packaging reduction. Journal of Cleaner Production.
9. John, J. S., et al. (2025). Towards a low-carbon future: Evaluating 3D printing's sustainability potential. Sustainability, 17(19), Article 8837. <https://doi.org/10.3390/su17198837>
10. Morales, M. A., et al. (2021). Development and characterization of rice husk and recycled polypropylene composite filaments for 3D printing. Polymers, 13(7), Article 1067.

11. Page, M. J., et al. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. BMJ, 372, Article n71. <https://doi.org/10.1136/bmj.n71>
12. Rabelo, L. S., et al. (2025). The future of sustainable packaging: Exploring biodegradable solutions through extrusion, 3D printing and agro-industry waste. Foods, 14(23), Article 4027.
13. SOLIDWORKS / Toshiba. (2025). Toshiba innovates packaging for speed, cost, and sustainability. Customer story. <https://www.solidworks.com/customer-story/toshiba-innovates-packaging-speed-cost-and-sustainability>
14. Sustainable Packaging Coalition. (2026). 2026 sustainable packaging trends report.
15. Witek-Krowiak, A., et al. (2024). Advanced packaging techniques .A mini-review of 3D printing in sustainable packaging. Materials, 17(12), Article 2997. <https://doi.org/10.3390/ma17122997>