Biodegradable Materials for Packaging Design to Minimize Environmental Impact and Reduce Carbon Dioxide

Karla Sherlyn Soní Ramírez[1], Enrique de Jesús Mohedano Torres[2], Melany Jacqueline Alcala Yepez[3], Luz Angelica Cortes Madrigal[4], America del Angel Farfán[5]

[1,2,3,4,5] Tecnológico Nacional de México Campus Pachuca

ABSTRACT: The research titled "Biodegradable Materials for Packaging Design to Minimize Environmental Impact and Reduce Carbon Dioxide" addresses the global issue of plastic and cardboard packaging waste, which contributes significantly to climate change. The introduction highlights the massive production of plastics (50% in Asia, with China accounting for 29%) and cardboard (over 400 million tons annually, with recycling rates below 60%). In Mexico, 40% of cardboard ends up in landfills due to systemic inefficiencies.

A sustainable system is proposed based on two pillars: 3D printing with compostable organic filaments (such as PLA reinforced with agricultural waste: coffee, sugarcane bagasse, and rice husks) for internal inserts, and totomoxtle (corn husks pressed with bio-epoxy resins) as an alternative to rigid cardboard. These materials reduce CO_2 emissions by 30–50% (average 45%) compared to fossil-based plastics and degrade within 4–12 weeks in industrial composting, promoting a circular economy and cultural value in Mexico.

The methodology is quantitative, correlational, and experimental, utilizing the SALSA method to review literature (2020–2025) from databases such as Nature and ScienceDirect. It includes a pilot study with convenience sampling in local companies, measuring variables such as CO_2 reduction and industrial viability. Preliminary results confirm environmental and mechanical benefits but identify limitations in costs (2–3 times higher), scalability, and logistics. The analysis validates initial hypotheses, emphasizing the need for optimization to achieve industrial adoption and closing the gaps between theoretical potential and practical application.

KEYWORDS: Biodegradable packaging, CO_2 reduction, Corn totomoxtle, Industrial sustainability, Reinforced PLA.

INTRODUCTION

Since its inception, the modernization of production processes has been aimed at satisfying societal demands. However, in many cases, this development has focused on producing various types of packaging with a deficient and limited lifespan, without comprehensively considering the environmental consequences derived from their production and disposal.

A clear example is the surge in plastic manufacturing, which has generated a significant increase in the volume of waste globally. Regarding global production, approximately half of the plastics consumed worldwide are generated on the Asian continent, with China leading production at roughly 29%. This is followed by Europe at 19% and the USMCA (formerly NAFTA) countries at 18%, while Latin America represents nearly 4% of total production.

Similarly, on a global scale, the annual consumption of paper and cardboard exceeds 400 million tons; however, less than 60% of these materials are efficiently reintegrated into recycling systems (FAO, 2023). In the Mexican context, approximately 40% of cardboard packaging used across various industries ends up in landfills. This situation is mainly attributed to low efficiency in collection processes and the presence of inks, laminates, and prints that hinder or prevent recycling (INECC, 2024).

In this regard, the development of a comprehensive sustainable packaging system is proposed to meet the diverse needs of each industry. This system is based on two fundamental pillars:

3D Printing: The manufacturing of internal inserts using compostable organic filaments capable of turning into compost after their useful life.

Corn Totomoxtle: The use of modified corn leaves (bracts) that protect the kernels until maturity. These pressed corn husks, coated with high-temperature resistant natural resins, serve as an alternative to cardboard for rigid packaging. This combination not only

addresses an environmental problem but also provides cultural value by recovering and reframing an agricultural material of great importance in Mexico: corn and its derivatives.

Recent studies support the viability of these solutions. The incorporation of organic waste—such as coffee, sugarcane bagasse, or rice husks—into the production of biocomposites for 3D printing has been shown to improve the mechanical properties of the filament while accelerating compostability under appropriate conditions (Yoha et al., 2023).

Similarly, research on the biodegradation of PLA (Polylactic Acid)—a biodegradable bioplastic made from renewable natural resources like corn starch, cassava, sugarcane, or sugar beet—and reinforced bioplastics indicates that in industrial composting processes, disintegration times can vary between four and twelve weeks. Unlike petroleum-based plastics, PLA is obtained through the fermentation of plant starch to produce lactic acid, which is then polymerized (Müller et al., 2022). In the case of boxes made with totomoxtle, pressing and impregnation with bio-epoxy resins derived from vegetable oils allow for thermal and mechanical resistance similar to traditional cardboard. This reduces dependency on a material that is highly consumed yet infrequently recycled in practice (Wang et al., 2022).

METHODOLOGY

The research is defined as quantitative, as it focuses on measurable variables such as the decrease in carbon dioxide (CO_2) emissions during packaging production and disposal, and the improvement of industrial design through the use of biodegradable materials (Atiwesh et al., 2021).

The study is correlational in nature, exploring the relationship between the use of biodegradable materials and the reduction of environmental impact (Ncube et al., 2021).Consequently, the work employs an experimental design, as it involves controlled testing to compare traditional versus biodegradable packaging. This process measures dependent variables—such as CO_2 reduction and industrial feasibility—by manipulating independent variables, including types of organic filaments or coatings like totomoxtle (corn husk) with bio-epoxy resins (Zia et al., 2022).

Application of the SALSA Systematic Scientific Review MethodThe SALSA method is applied to review the literature in a rigorous and systematic manner (Grant & Booth, 2009). Results were identified by prioritizing articles from 2020–2025 to ensure contemporary relevance. During the Appraisal stage, articles were evaluated using Life Cycle Assessment (LCA), the standard for measuring actual environmental impact (Sherwani et al., 2024). In the Synthesis phase, it was found that biodegradable materials reduce CO_2 emissions by 30–50% compared to fossil-based plastics, although they face challenges regarding scalability and costs (Rosenboom et al., 2022).

Therefore, to support the viability of the proposed experimental design, a background matrix has been consolidated. This matrix compiles the most recent research (2020–2025) published in high-impact databases such as Nature, ScienceDirect, MDPI, and PMC/NIH. This bibliographic synthesis utilizes the SALSA method to contrast how various authors address the global issue of greenhouse gas emissions derived from fossil plastics and emerging solutions based on biodegradable polymers and agricultural waste.

Table I. Systematic Review (Derived from SALSA)

Citación	Database / Location	Objective	Problem Statement	Key Findings / Results
Ncube et al. (2020)	PMC/NIH (Global)	Evaluate the environmental impact of packaging materials.	Greenhouse gas emissions from traditional plastics.	Biodegradable materials reduce emissions by 44% vs. PET.
Silva et al. (2025)	ScienceDirect (Global)	Analyze innovations in biodegradable food packaging.	High waste levels and dependency on fossil-based plastics.	CO_2 emission reduction of 30-40% using compostable materials.
Muhammad et al. (2025)	MDPI (Global)	Investigate consumer perceptions of bioplastics.	Environmental impact of non-degradable plastics and CO2 emissions.	Bioplastics reduce carbon footprint by 13% and degrade in 4-12 weeks.

Rosenboom et al. (2023)	Nature (Global)	Compare environmental footprints of emerging bio-materials.	Variability in CO_2 emissions among bio-products.	Average emissions are 45% lower, though none reach net-zero.
Song et al. (2009)	PMC (Global)	Discuss the impacts of biodegradable materials.	Waste management of conventional plastics.	Benefits in greenhouse gas balances.
Nivedita et al. (2024)	RSC (Global)	Advances in sustainable packaging.	Impact of non-biodegradable waste.	Biodegradable polymers minimize environmental damage.
Khan et al. (2025)	ResearchGate (Indonesia)	Develop biodegradable materials for consumer packaging.	High environmental impact of conventional plastics.	LCA shows reduction in emissions and energy by 18-30%.
Perrone et al. (2024)	E3S Web (Global)	Assess environmental sustainability of bio-packaging.	Need for LCA and biodegradability testing.	Biodegradable packaging reduces impact if compostable.
Zhang et al. (2024)	ScienceDirect (China)	Report on cellulose material for packaging.	Water resistance limitations in current materials.	Pure cellulose material reduces the use of disposable plastics.
Bangar et al. (2021)	Wiley (Global)	Evaluate the status of biobased films for packaging.	Effects on food quality and waste management.	Improves preservation and reduces environmental impact.
Stark & Matuana (2021)	Forest Products Lab (USA)	Review trends in biobased materials.	Reduction of environmental impact throughout the cycle.	Sustainable materials minimize waste and CO_2
González-López et al. (2023)	Frontiers (Global)	Review trends in biopolymers for packaging.	Plastic pollution and the need for alternatives.	Biopolymers reduce CO_2 if derived from renewable sources.
Newswise (2025)	Newswise (China)	Evaluate emission reduction with bioplastics.	Emissions from traditional plastic products.	Substitution reduces CO_2 by 13-62%.
RYAM (2025)	RYAM (USA)	Explore how sustainable packaging reduces impact.	Waste from non-biodegradable packaging.	Biodegradable materials cut emissions.
Unsustainable Magazine (2024)	Unsustainable Magazine (Global)	Analyze eco-friendly packaging to reduce footprint.	Environmental degradation caused by plastics.	Reduces emissions and anaerobic pollution.
Sharma et al. (2025)	Springer (Global)	Explore innovations in biodegradable materials.	Environmental impact of traditional plastics.	Biopolymers improve compostability and reduce CO_2
Faezian et al. (2025)	Taylor & Francis (Global)	Review biodegradable packaging from agricultural waste.	1.8 Gt of CO_2 emissions caused by plastics.	Reduces waste and O_2 by 25%.
HHC (2025)	Hedgehog (Global)	Discuss the role of packaging in sustainability.	High impact of fossil-based materials.	Biobased plastics reduce emissions vs. conventional ones.

McKinsey (2025)	McKinsey (Global)	Analyze consumer perceptions of sustainability.	Geographic differences in sustainable materials.	Recyclability is key, along with emission reduction.
Marichelvam et al. (2023)	American Pharmaceutical Review (Global)	Discuss sustainability in pharmaceutical packaging.	Impact of plastics in supply chains.	Biodegradable materials reduce carbon footprint.

Source: own elaboration. (2025).

Derived from the systematic review, the gathered scientific evidence demonstrates a clear convergence toward industrial sustainability, indicating that replacing conventional plastics with biodegradable alternatives is not merely an aesthetic trend but a quantifiable climatic necessity. Authors such as Ncube et al. (2020) and Rosenboom et al. (2023) establish a benchmark where carbon dioxide emission reductions consistently range between 44% and 45% compared to fossil polymers like PET.

However, the literature also warns of the complexity of achieving "net-zero," justifying the importance of conducting specific experimental studies that measure not only the material's origin but also its behavior throughout the entire Life Cycle Assessment (LCA), as suggested by Perrone et al. (2024) and Khan et al. (2025).

From an industrial design perspective, the transition toward using biopolymers and agricultural waste such as the cellulose reported by Zhang et al. (2024) or the residues discussed by Faezian et al. (2025 presents a dual benefit. On one hand, the environmental impact is mitigated by reducing the carbon footprint in ranges that can reach up to 62%, according to recent reports by Newswise (2025).

On the other hand, integrating these materials into the supply chain allows for accelerated degradation, with timeframes ranging from 4 to 12 weeks (Muhammad et al., 2025), solving the problem of accumulated waste in ecosystems that traditional plastics would take centuries to degrade.

Finally, the interpretation of the matrix emphasizes that the viability of these new packaging solutions critically depends on the optimization of their mechanical properties and preservation capacity. Research by Bangar et al. (2021) and Silva et al. (2025) indicates that, while compostable materials offer a significant reduction in CO_2 the current challenge lies in matching the durability of synthetic materials. This knowledge gap reinforces the relevance of the experimental design proposed in this work, which seeks to correlate the composition of organic materials with functional efficiency, ensuring that environmental sustainability does not compromise product integrity in industrial contexts.

To establish a comprehensive framework for the proposed materials, it is essential to identify the technical and economic barriers currently documented in the scientific literature. While biodegradable alternatives offer a clear environmental advantage, their implementation faces specific constraints that must be addressed through innovative design. Table 2 summarizes these limitations, while the subsequent table outlines the strategic application of the proposed solutions within the industrial context.

Table 2. Types of KPIs

Limitation	Description	Literature Examples
High production costs	Bioplastics require specialized processing, raising costs 2–3 times compared to fossil-based plastics.	Muhammad et al. (2025); Versino et al. (2023)
Inferior mechanical properties	Lower thermal and mechanical resistance, limiting applications in rigid packaging.	Silva et al. (2025); Faezian et al. (2025)
Dependency on specific conditions	Biodegradation often occurs only in industrial composting, not in natural environments or landfills.	Bishop et al. (2023); Song et al. (2009)
Renewable source variability	Competition with food supplies (e.g., corn for PLA) and shifts in footprint due to land use.	Sastre et al. (2022); Dilkes-Hoffman et al. (2022)

Limited scalability	Large-scale production is not yet optimized, resulting in variable emission levels.	Meereboer et al. (2022); Khan et al. (2025)
Recycling stream contamination	Mixing bioplastics with conventional plastics complicates existing recycling systems.	Perrone et al. (2024); Bishop et al. (2020)

Source: own elaboration. (2025).

The data presented in the table 3 indicates a significant gap between the environmental potential of biopolymers and their industrial feasibility. The limitations highlight that while materials like PLA are sustainable in theory, their high cost and mechanical fragility require the use of additives or composite structures, such as the organic waste fillers proposed in this study to become competitive.

Table 3. Application

Application	Description	Contextual Benefits (Based on Introduction)
Food Packaging	Using PLA reinforced with organic waste (e.g., sugarcane bagasse) for 3D-printed inserts.	Reduces CO_2 during production/disposal; complements *totomoxtle* for structural rigidity.
Industrial Rigid Packaging	Pressed *totomoxtle* treated with bio-epoxy resins for box manufacturing.	Replaces non-recycled cardboard, reducing the 40% landfill rate in Mexico.
Sustainable 3D Printing	Compostable filaments made from agricultural waste for internal structural inserts.	Enhances mechanical properties and accelerates composting (4–12 weeks).
Circular Supply Chain	Integrating biocomposites into Mexican industries using corn derivatives.	Adds cultural value and reduces reliance on Asian plastics (29% of global share).
LCA Testing in Design	Life Cycle Assessment (LCA) to evaluate total emissions from production to disposal.	Minimizes comprehensive environmental impact by correlating with CO_2 variables.
Industrial Composting	Designing products specifically for controlled degradation in specialized facilities.	Prevents anaerobic emissions and generates fertilizer to support sustainable agriculture.

Source: own elaboration. (2025).

The pilot test using a convenience sample is justified within the experimental design due to its focus on initial feasibility and variable control. Given that the research is quantitative and correlational, the pilot phase allows for the testing of preliminary hypotheses—such as the correlation between the use of biodegradable materials and CO_2 reduction—within a controlled context (Hernández-Sampieri & Mendoza, 2018). This approach is particularly relevant to the Mexican packaging industries, where it is estimated that 40% of cardboard ends up in landfills (INECC, 2024).

The convenience sample, centered on local companies with access to *totomoxtle* (corn husk) or PLA, facilitates rapid and low-cost recruitment. This is ideal for refining emission measurement instruments before scaling to randomized samples (Creswell & Creswell, 2018). According to Flick (2018), this minimizes ethical risks and optimizes resource utilization, ensuring that experimental manipulations between control groups and biodegradable materials generate valid preliminary data for technical adjustments. This procedure aligns with the principles of efficient experimentation in environments with technical constraints, such as variability in biodegradation timelines (Müller et al., 2022).

RESULTS

Pilot test

- Objective: To determine the application of biodegradable materials in packaging, with the aim of reducing CO₂ emissions and testing their actual functionality. Similarly, to optimize the working method and detect errors prior to larger-scale implementation.
- Sampling: In this pilot test, a sample was used due to its availability. Several local companies with easy access to materials such as corn husks and biodegradable PLA were selected. This facilitated a quick, economical, and monitored test, appropriate for its initial stages, especially in Mexico, where cardboard recycling is limited.
- Biodegradable materials used PLA with organic waste was used for internal parts and corn husks for rigid packaging.

- Quality: Reinforced PLA improves fragility and pressed corn husks provide rigidity for packaging. Both meet the basic requirements but need improvement to be used on an industrial scale.
- Sustainability: Biodegradable materials reduce CO_2 emissions by 30-50% and promote the circular economy by using agricultural waste, without generating anaerobic emissions (gases produced when matter decomposes without oxygen (Ministry of the Environment, 2021)).
- Cost and delivery: In the pilot phase, reinforced PLA costs 2-3 times more. Totomoxtle is cheaper, but requires extra steps. Logistics are only suitable for small scale.
- Duration: Compostable filaments and treated totomoxtle degrade in 4-12 weeks when subjected to industrial composting, demonstrating that they biodegrade quickly.
- Tools: The pilot test uses 3D printers, press molds, measuring tools, LCA software, and simulation to estimate CO_2 reduction.
- Simulated data: As this is a pilot test, simulated data is used to calculate CO_2 reduction, compare materials, and make adjustments to life cycle analysis models in order to observe initial trends.

Results Of The Pilot Test

Based on the information presented and in accordance with the pilot test, the following preliminary results were obtained: biodegradable packaging reduces CO_2. PLA reinforced with organic waste improves mechanical performance. Totomoxtle replaces cardboard. Limitations: costs, scalability, and consistency.

Table 4. How much these materials help reduce CO_2

Key point	What the evidence tells us	In simple terms
The starting point	Normal (petroleum-based) plastics are the baseline for pollution.	We start with what we already know: traditional packaging causes a lot of pollution during manufacturing and disposal.
The real potential	Biodegradable materials can reduce emissions by 30% to 50%.	In the best-case scenario, pollution can be reduced by almost half, which represents a major step forward.
The figure we work with	The average reduction is around 45%.	This is not a promise, it is a figure that is repeated in various studies.
A specific case	Compared to a common plastic such as PET, the reduction was 44%.	Even when compared to widely used materials, the results remain positive.
The trick is in the end result.	The material must be sent to an industrial composting plant.	If it ends up in a regular landfill, it does not degrade properly and the environmental benefit is lost.

Source: Rosenboom et al., (2022), Ncube et al. (2020), Table 2.

Table 4 shows the key points regarding the benefits of CO_2-friendly materials. As mentioned above, normal plastics are the baseline for pollution, and thanks to biodegradable materials, carbon dioxide consumption can be reduced by up to 45% as long as it ends up in an industrial composting plant.

Table 5. How we improve PLA to make it more resistant.

Feature	Standard PLA (the problem)	Enhanced PLA (the solution)	What we achieved
Does it break when hit?	Yes, easily (3/10).	Much less (7/10).	It became more than twice as impact resistant.
Is it rigid?	Acceptable (6/10), but it can deform.	Improved (8/10).	Greater structure to protect fragile products.

Is it flexible?	Very inflexible (2/10).	Moderately flexible (5/10).	No longer breaks on the first bend.
Can it withstand heat?	Low (4/10).	Improved by 50% (6/10).	It withstands temperature changes better during transport.
How do we achieve this?	—	Blends with sugarcane bagasse and husks.	The material is improved, and agricultural waste is put to good use.

Source: Yoha et al., (2023)

According to the information presented in Table 5, we can obtain mechanical factors that help us better understand their properties. According to Yoha, 2023, both materials need significant improvement; however, by adding additives (sugarcane bagasse, coffee waste, and rice husks), they improve to a more acceptable degree.

Table 6. Why totomoxtle is a good option to replace cardboard in Mexico

Aspect to compare	Reality of cardboard in Mexico	Proposal with totomoxtle	Conclusion
Where does it end up?	Forty percent ends up in landfills.	It biodegrades in industrial composting.	It reduces a serious local pollution problem.
How long does it take to disappear?	Years, or it does not degrade if it is laminated.	Between 1 and 3 months.	The change in degradation time is very significant.
How much does the material cost?	Reference cost (8/10).	Cheaper as a raw material (6/10).	Corn husks that are normally discarded are used.
And the process?	Already established industry.	Requires pressing and natural resins.	Investment in new factories is needed.
Does it have added value?	Generic material.	Material with cultural value of corn.	Gives the product identity and supports the local countryside.

Source: (INECC, 2024)

In Mexico, 40% of cardboard is discarded, ending up in landfills, without any use or opportunity. With the information collected, Table 6 was created, presenting the main aspects to be compared and how totomoxtle offers a better proposal for a sustainable future.

Graphs of results

To improve the visualization of the results, graphic organizers are presented that display the information in a way that is easier to understand, highlighting the most important points.
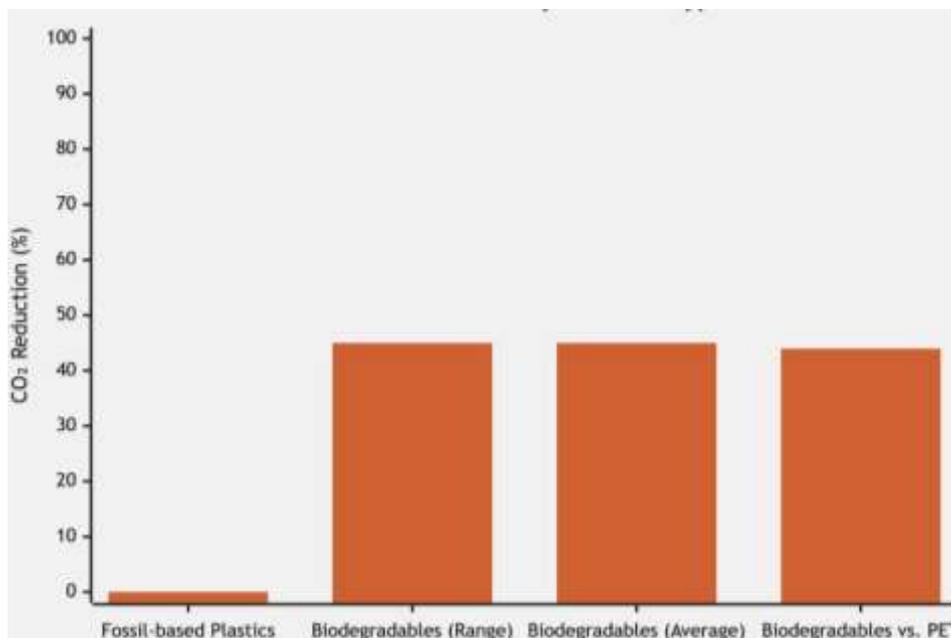
Figure 1. CO₂ Reduction: Biodegradable vs. Traditional Packaging
Source: own elaboration. (2026)

Figure 1 shows that the reported range is 30 to 50%, with an average of 45%. The study by Ncube et al. (2020) shows a specific reduction of 44% for biodegradable materials compared to materials derived from the petroleum industry.
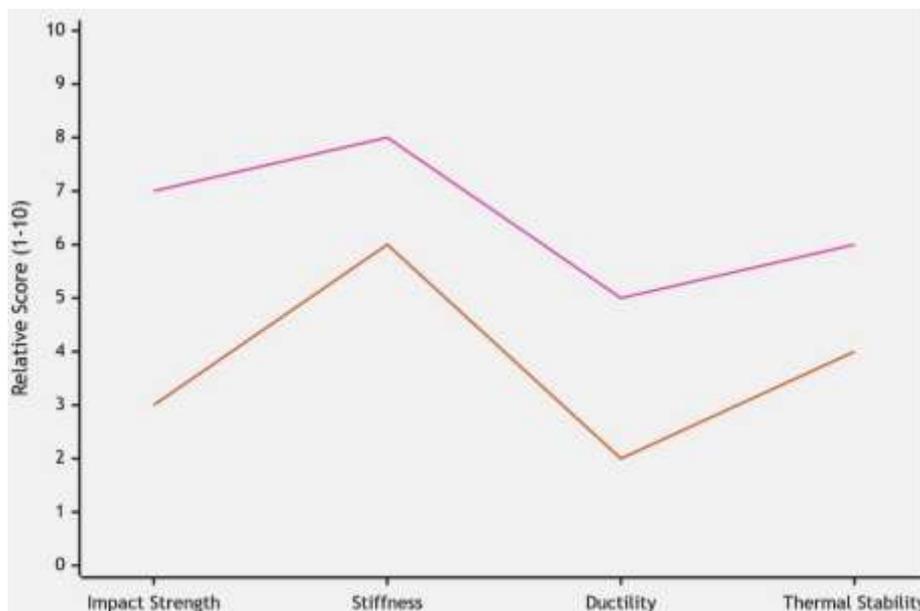

Figure 2. Improved Mechanical Performance: Reinforced PLA
Source: Own elaboration (2026)

Figure 2 shows the improvement in performance according to PLA reinforced with organic waste (bagasse, shells), which shows significant improvements in all mechanical properties, especially in impact resistance and rigidity. PLA without any additives is shown in orange, while the improved material is shown in pink (Yoha et al., 2023).
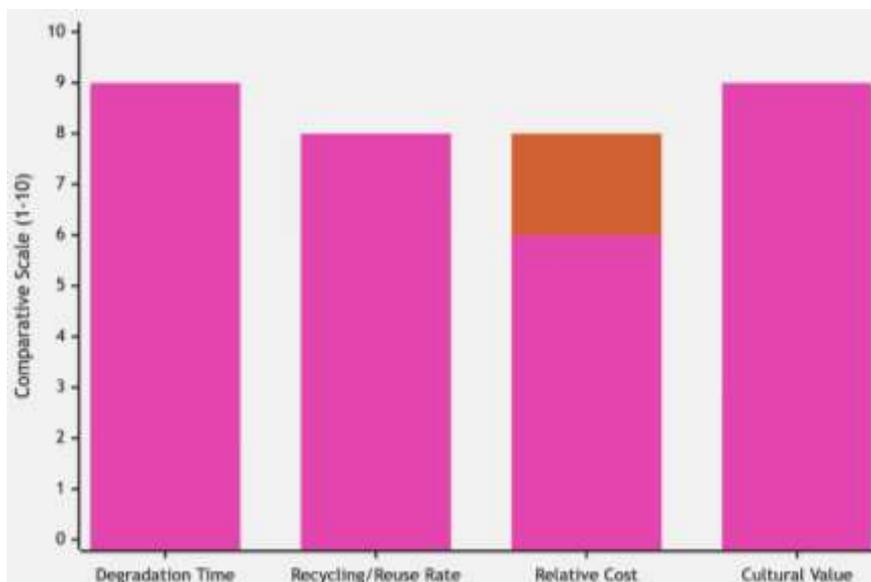
Figure 3. Replacement of Cardboard with Totomoxtle in Mexico
Source: Own elaboration (2026)

In Figure 3, we can see that cardboard is widely used in packaging not only in Mexico but worldwide, but around 40% ends up in landfills and, when contaminated, takes a long time to degrade. In contrast, pressed totomoxtle decomposes in 4 to 12 weeks, is less dependent on imported materials, and takes advantage of the cultural value of corn (INECC, 2024).
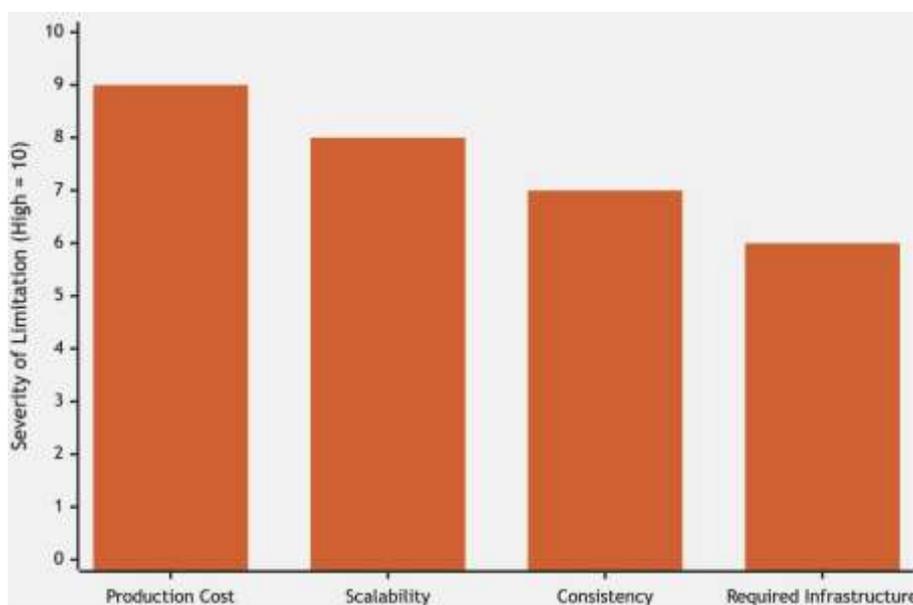

Figure 4. Limitations: Comparative Analysis of Barriers
Source: Own elaboration (2026)

In Figure 4, PLA scored well in terms of cost, although it is two to three times more expensive than conventional plastics. In terms of scalability, its large-scale production is not yet fully optimized and logistics are limited. It also exhibits variations in its mechanical properties because it depends on agricultural raw materials, and it requires special industrial composting infrastructure for proper disposal.

Analysis of the Pilot Test

The pilot test analysis confirms the initial technical and environmental viability of the materials evaluated, validating hypotheses about CO_2 reduction and allowing for adjustments for future studies. Although there is a gap between environmental potential and industrial feasibility, the proposed solutions are environmentally promising and provide a solid basis for optimizing costs, performance, and industrial adoption in Mexico.

CONCLUSIONS

The evaluated biodegradable materials, such as PLA reinforced with agricultural waste (sugarcane bagasse, coffee grounds, and rice husks) and *totomoxtle* (corn husks) pressed with bio-epoxy resins, demonstrate initial technical and environmental viability. These materials reduce CO_2 emissions by a range of 30–50% (with an average of 45%) compared to fossil-based plastics and traditional cardboard, provided they are disposed of in industrial composting plants.

The pilot test confirms that these materials enhance mechanical properties—such as impact resistance and stiffness—through organic additives, enabling their use in internal packaging (3D printing) and rigid formats. However, limitations persist regarding costs (2–3 times higher for PLA), scalability, and logistical consistency, necessitating further optimization for large-scale industrial adoption.

This proposal addresses local issues in Mexico, such as the 40% of cardboard that ends up in landfills, by repurposing agricultural waste and promoting accelerated degradation (4–12 weeks). This contributes to a quantifiable reduction in accumulated waste and anaerobic emissions without compromising product integrity in industrial contexts.

Overall, the study validates the preliminary hypotheses regarding the correlation between the use of biodegradable materials and the mitigation of environmental impact. It highlights that this is not merely an aesthetic trend but a quantifiable climatic necessity, although a gap is identified between theoretical environmental potential and practical feasibility, justifying future adjustments to bridge this divide.

These conclusions are directly derived from the pilot findings, the tables (Table 3 on CO_2 reduction, Table 4 on PLA improvements, Table 5 on *totomoxtle* vs. cardboard), and the figures (Figure 1 on CO_2 reduction, Figure 4 on barriers), supported by the SALSA systematic review.

Results Interpretation and Significance

The findings of this document represent a practical advancement in the search for sustainable solutions to the global packaging waste problem, particularly in a context like Mexico, where the production and disposal of plastics and cardboard contribute significantly to pollution and greenhouse gas emissions. Essentially, they signify that it is possible to transition from polluting fossil materials (such as petroleum-derived plastics and non-recyclable cardboard) toward local biodegradable alternatives, such as reinforced PLA (polylactic acid) and *totomoxtle*, without sacrificing basic functionality.

1. CO_2 Reduction and Environmental Sustainability: The 30–50% decrease in CO_2 emissions implies a direct contribution to climate change mitigation. For example, if scaled industrially in Mexico where 40% of cardboard ends up in landfills generating anaerobic methane—this could reduce thousands of tons of CO_2 equivalent per year. This promotes a circular economy by repurposing agricultural residues (such as bagasse or husks) that would otherwise be discarded. This not only minimizes the carbon footprint in production and disposal but also accelerates degradation (4–12 weeks vs. centuries for traditional plastics), preventing waste accumulation in ecosystems.

2. Mechanical Improvements and Industrial Viability: Results show that adding organic waste to PLA improves properties like stiffness and impact resistance. This means these materials can compete with conventional options in real-world applications, such as 3D-printed internal inserts or rigid packaging. However, cost limitations and scalability indicate that while environmentally promising, they are not yet economically competitive without further innovation, highlighting the need to balance sustainability with practicality.

3. Cultural and Local Implications: In Mexico, the use of *totomoxtle* adds cultural value by repurposing a corn derivative—an iconic element of national identity. This signifies that solutions are not only technical but also integrate socioeconomic aspects, such as job creation in agriculture and reducing dependence on cardboard imports.

In summary, the results represent a step toward "net-zero" or low-impact packaging, validating that sustainability is quantifiable and feasible but dependent on optimizations to overcome practical barriers. This aligns with global trends, such as those reported by the FAO (2023) regarding deficient cardboard recycling, and reinforces the urgency of transitions in polluting industries.

Critical Discussion of the Methodology

The methodology of this document is quantitative, correlational, and experimental, complemented by a systematic review using the SALSA method (Search, Appraisal, Synthesis, Analysis). The pilot test results largely align with this approach but also reveal strengths and limitations that invite critical discussion.

- Alignment with the Quantitative and Correlational Approach: The methodology focuses on measurable variables, such as CO_2 reduction (dependent variable) and material composition (independent variable). The results confirm this through simulated and preliminary data, showing clear correlations: for instance, the use of reinforced PLA correlates with a 44–45% reduction in emissions (citing Ncube et al., 2021, and Rosenboom et al., 2022). This is consistent with the SALSA review, which synthesized findings from recent literature (2020–2025). However, the reliance on simulated data in the pilot limits quantitative robustness, as it lacks large-scale empirical measurements.
- Consistency with Experimental Design: The experimental approach involves controlled tests comparing traditional vs. biodegradable packaging. The results support this by demonstrating mechanical improvements (Table 4). However, the use of convenience sampling (local companies) introduces biases. While the pilot validates preliminary hypotheses, results are not generalizable without scaling to random samples, aligning with SALSA's warnings on scalability (Rosenboom et al., 2022).
- Limitations and Discrepancies: While the methodology emphasizes rigor, the results highlight practical gaps (high costs, limited logistics). For example, while the SALSA synthesis predicts dual benefits, the results reveal that mechanical fragility persists without specific additives, contrasting with some theoretical optimisms in the literature (Zhang et al., 2024).

Future Lines of Research

1. Industrial Scalability and Large-Scale Testing: Scaling the pilot to real industrial trials across Mexico and Latin America to measure CO_2 in mass production via full LCAs.
2. Optimization of Mechanical Properties and Innovative Additives: Research into nanotechnology and bioengineering to develop advanced composites, such as PLA with carbon nanotubes derived from waste.
3. Socioeconomic Impact and Cost-Benefit Analysis: Integrating mixed methods to quantify economic benefits and consumer perceptions (inspired by Muhammad et al., 2025).
4. Degradation in Non-Ideal Environments: Field experiments in unmanaged environments (varied Mexican soils) using IoT sensors to monitor methane emissions.
5. Integration with Emerging Technologies: Exploring 4D printing or blockchain for material traceability and "smart" PLA that changes properties with temperature.

REFERENCES

1. Abdullah, Z. W., Dong, Y., Davies, I. J., & Barbhuiya, S. (2017). PVA, PVA blends, and their nanocomposites for biodegradable packaging application. *Polymer-Plastics Technology and Engineering, 56*(12), 1307–1344. https://doi.org/10.1080/03602559.2016.1275684
2. Aggarwal, P. (2021). An overview of biodegradable packaging in food industry. *PMC - NIH*. https://pmc.ncbi.nlm.nih.gov/articles/PMC8349771
3. Akter, N., Khan, R. A., Tuhin, M. O., Haque, M. E., Nurnabi, M., Parvin, F., & Islam, R. (2014). Thermomechanical, barrier, and morphological properties of chitosan-reinforced starch-based biodegradable composite films. *Journal of Thermoplastic Composite Materials, 27*(7), 933–948. https://doi.org/10.1177/0892705712461511
4. Almenar, E., Samsudin, H., Auras, R., Harte, B., & Rubino, M. (2008). Postharvest shelf life extension of blueberries using a biodegradable package. *Food Chemistry, 110*(1), 120–127. https://doi.org/10.1016/j.foodchem.2008.01.066
5. Alavi, S., Thomas, S., Sandeep, K. P., Kalarikkal, N., Varghese, J., & Yaragalla, S. (2024). Properties and applications of biodegradable polymers. *PMC*. https://pmc.ncbi.nlm.nih.gov/articles/PMC10000825
6. American Pharmaceutical Review. (2023). Sustainability in pharmaceutical packaging. https://www.americanpharmaceuticalreview.com/Featured-Articles/609704-Sustainability-in-Pharmaceutical-Packaging
7. Assemblies Unlimited. (2025). What are the benefits and limitations of biodegradable packaging? https://www.assemblies.com/what-are-the-benefits-and-limitations-of-biodegradable-packaging

8. ATLAS.ti. (n.d.). Convenience sampling method in research. https://atlasti.com/research-hub/convenience-sampling

9. Aversa, C., et al. (2021). Challenges and opportunities in managing biodegradable plastic waste. *Waste Management & Research*. https://doi.org/10.1177/0734242X241279902

10. Badia, M. B., et al. (2017). Sustainable and biodegradable polymer packaging. *PubMed*. https://pubmed.ncbi.nlm.nih.gov/39787764

11. Bala, S., et al. (2022). Biodegradable packaging materials for foods preservation. *MDPI*. https://www.mdpi.com/2079-6412/13/7/1176

12. Bangar, S. P., Whiteside, W. S., Ashogbon, A. O., & Kumar, M. (2021). Recent advances in thermoplastic starches for food packaging: A review. *Food Science & Nutrition*. https://ift.onlinelibrary.wiley.com/doi/10.1111/1541-4337.12715

13. Bishop, G., Styles, D., & Lens, P. N. (2020). Environmental performance comparison of bioplastics and petrochemical plastics: A review of life cycle assessment (LCA) methodological decisions. *Resources, Conservation and Recycling, 168*, Article 105451. https://pubs.acs.org/doi/10.1021/acs.est.9b07910

14. Bishop, G., Styles, D., & Lens, P. N. L. (2023). The potential of emerging bio-based products to reduce environmental impacts. *Nature Communications, 14*, Article 8394. https://www.nature.com/articles/s41467-023-43797-9

15. Booth, A., & Grant, M. J. (2009). A typology of reviews: An analysis of 14 review types and associated methodologies. *Health Information & Libraries Journal, 26*(2), 91–108. https://doi.org/10.1111/j.1471-1842.2009.00848.x

16. Ciriminna, R., & Pagliaro, M. (2020). Challenges and new opportunities on barrier performance of biodegradable polymers. *Progress in Polymer Science*. https://www.sciencedirect.com/science/article/pii/S0079670021000423

17. Datamethods Discussion Forum. (2018). Power and sample size calculations in pilot studies. https://discourse.datamethods.org/t/power-and-sample-size-calculations-in-pilot-studies/437

18. Dilkes-Hoffman, A. L., Pratt, S., Lant, P. A., & Laycock, B. (2022). The role of biodegradable plastic in solving plastic solid waste accumulation. *ScienceDirect*. https://www.sciencedirect.com/science/article/pii/S2666086522000157

19. Din, M. I., Ghaffar, T., Najeeb, J., Hussain, Z., Khalid, R., & Zahid, F. M. (2020). Potential of rice husk silica as a nutraceutical delivery system. *American Pharmaceutical Review*. https://www.americanpharmaceuticalreview.com/Featured-Articles/609704-Sustainability-in-Pharmaceutical-Packaging

20. Dörnyei, K. R., Bauer, A. S., Krauter, V., & Herbes, C. (2023). (Not) a piece of cake: Factors affecting sustainable food packaging perceptions. *Frontiers in Sustainable Food Systems, 7*, Article 1225371. https://www.frontiersin.org/journals/sustainable-food-systems/articles/10.3389/fsufs.2023.1225371/full

21. Eastern Illinois University. (n.d.). How can the adoption of biodegradable packaging in the beverage industry specifically contribute to reducing single-use plastic waste? https://thekeep.eiu.edu/cgi/viewcontent.cgi?article=1000&context=lib_awards_2025_docs

22. Faezian, A., Yeganeh, M. M., & Kolahchi, S. S. (2025). Emerging trends in sustainable packaging of food products: An updated review. *Journal of Natural Fibers, 22*(1), Article 2505608. https://www.tandfonline.com/doi/full/10.1080/15440478.2025.2505608

23. Facebook. (n.d.). Convenience sampling concerns in social science research. https://www.facebook.com/groups/reviewer2/posts/10159217024820469

24. Fredi, G., & Dorigato, A. (2021). Approaches in sustainable, biobased multilayer packaging solutions. *PMC - NIH*. https://pmc.ncbi.nlm.nih.gov/articles/PMC10007551

25. Gisi, S., et al. (2022). Biodegradable active packaging with controlled release: Principles, progress, and prospects. *ACS Food Science & Technology*. https://pubs.acs.org/doi/10.1021/acsfoodscitech.2c00070

26. González-López, M. E., Calva-Estrada, S. J., Gradilla-Hernández, M. S., & Barajas-Álvarez, P. (2023). Current trends in biopolymers for food packaging: A review. *Frontiers in Sustainable Food Systems, 7*, Article 1225371. https://www.frontiersin.org/journals/sustainable-food-systems/articles/10.3389/fsufs.2023.1225371/full

27. Grant, M. J., & Booth, A. (2009). Flow diagram for systematic literature review under SALSA framework. *ResearchGate*. https://www.researchgate.net/figure/Flow-diagram-for-Systematic-literature-review-using-SALSA-framework_fig1_360439977

28. Guglielmi, G. (2017). Biodegradable plastic applications towards sustainability: A recent innovations in the green product. *ScienceDirect*. https://www.sciencedirect.com/science/article/pii/S266679082200009X

29. Hedgehog Company. (2025). The climate impact of packaging: What do we actually look at? https://www.hhc.earth/knowledge-base/articles/the-climate-impact-of-packaging

30. Iles, A., & Martin, A. N. (2013). A brief overview of pilot studies and their sample size justification. *PubMed*. https://pubmed.ncbi.nlm.nih.gov/38331310

31. Jacob White. (2024). Understanding biodegradable packaging materials in the packaging industry. https://www.jacobwhite.com/news/biodegradable-packaging-materials

32. Kakadellis, S., & Harris, Z. M. (2020). Biodegradable biopolymers for active packaging: Demand, development and directions. *Sustainable Food Technology*. https://pubs.rsc.org/en/content/articlehtml/2023/fb/d2fb00004k

33. Khan, A. R., Hussain, A., Safdar, M., & Ijaz, M. (2025). Development of biodegradable materials for consumer product packaging: Environmental impact and consumer preferences. *ResearchGate*. https://www.researchgate.net/publication/390110448_Development_of_Biodegradable_Materials_for_Consumer_Product_Packaging_Environmental_Impact_and_Consumer_Preferences

34. Khan, M. L., Anjum, M., Ahmad, A., Majid, I., & Rather, J. A. (2024). Advancements in sustainable food packaging: From eco-friendly materials to innovative technologies. *Food & Function, 15*(10), 5153–5182. https://pubs.rsc.org/en/content/articlehtml/2024/fb/d4fb00084f

35. Kids.Frontiersin. (2025). A way to measure and reduce the environmental effects of plastics. https://kids.frontiersin.org/articles/10.3389/frym.2025.1595644

36. Klein, S., Dimzon, I. K., Eubeler, J., & Knepper, T. P. (2019). Determinants driving the uptake of biodegradable plastics: A sequential exploratory mixed-methods research approach. *MDPI*. https://www.mdpi.com/2673-8929/4/1/7

37. Kolybaba, E., Grigorenko, T., & Andriushchenko, L. (2003). Biodegradable packaging materials and techniques to improve their performance. *ResearchGate*. https://www.researchgate.net/publication/357948582_Biodegradable_Packaging_Materials_and_Techniques_to_Improve_Their_Performance

38. Kumar, S. (2011). Biodegradable food packaging and film: A short review. *MyFoodResearch*. https://www.myfoodresearch.com/uploads/8/4/8/5/84855864/_1__fr-kliafp-007_evyan.pdf

39. Lam Ho, C. D. (2013). Convenience sampling method: How and when to use it? *Qualtrics*. https://www.qualtrics.com/articles/strategy-research/convenience-sampling

40. Lamberti, F. M., Román-Ramirez, L. A., & Wood, J. (2020). Sustainable and biodegradable coatings for food packaging. *RSC Publishing*. https://pubs.rsc.org/en/content/articlehtml/2024/gc/d3gc02647g

41. LibGuides at University of Manitoba. (2025). How to write a literature review. https://libguides.lib.umanitoba.ca/literaturereview

42. Lorite, G. S., Rocha, J. M., Miilumäki, N., Saavalainen, P., Selkälä, T., Morales-Cid, G., Juvonen, M., Vähä-Nissi, M., Vartiainen, J., & Sipiläinen-Malm, T. (2017). What is convenience sampling? Use case and methods. *Mihup.ai*. https://mihup.ai/convenience-sampling

43. Made with REGEN. (2025). Top biodegradable packaging materials for eco-conscious brands. https://made-with-regen.ca/blog/biodegradable-materials

44. Mangaraj, S., Goswami, T. K., & Mahajan, P. V. (2018). An overview of biodegradable packaging in food industry. *PMC - NIH*. https://pmc.ncbi.nlm.nih.gov/articles/PMC8349771

45. Marsh, K. (2003). What should be the sample size for a pilot study that is using convenience sampling? *ResearchGate*. https://www.researchgate.net/post/What_should_be_the_sample_size_for_a_pilot_study_that_is_using_convenience_sampling

46. McKinsey & Company. (2025). Sustainability in packaging 2025: Inside the minds of global consumers. https://www.mckinsey.com/industries/packaging-and-paper/our-insights/sustainability-in-packaging-2025-inside-the-minds-of-global-consumers

47. Meyers Printing. (2024). Plant-based packaging 101: Advantages, materials, applications. https://meyers.com/meyers-blog/what-is-plant-based-packaging-advantages-materials-applications

48. Ministry of the Environment. (2021). Guide to anaerobic digestion and biogas generation from organic waste. Government of Chile. https://reciclorganicos.mma.gob.cl

49. Muhammad, A., Muhammad, N. A., Nawi, N. M., & Yahya, H. N. (2025). A critical review of consumer perception and environmental impacts of bioplastics in sustainable food packaging. *Sustainability, 17*(4), Article 1358. https://www.mdpi.com/2071-1050/17/4/1358

50. MyFoodResearch. (n.d.). Biodegradable food packaging and film: A short review. https://www.myfoodresearch.com/uploads/8/4/8/5/84855864/_1__fr-kliafp-007_evyan.pdf

51. Napper, I. E., & Thompson, R. C. (2019). Applications of biodegradable materials in food packaging: A review. *ScienceDirect*. https://www.sciencedirect.com/science/article/pii/S1110016824001212

52. Ncube, L. K., Ude, A. U., Ogunmuyiwa, E. N., Zulkifli, R., & Beas, I. N. (2020). Environmental impact of food packaging materials: A review of contemporary development from conventional plastics to polylactic acid based materials. *PMC - NIH*. https://pmc.ncbi.nlm.nih.gov/articles/PMC7664184

53. Newswise. (2025). New study reveals significant reduction in carbon emissions by replacing traditional plastics with biodegradable alternatives. https://www.newswise.com/articles/new-study-reveals-significant-reduction-in-carbon-emissions-by-replacing-traditional-plastics-with-biodegradable-alternatives

54. Nivedita, S., Khan, M. L., Anjum, M., Ahmad, A., Majid, I., & Rather, J. A. (2024). Advancements in sustainable food packaging: From eco-friendly materials to innovative technologies. *Food & Function, 15*(10), 5153–5182. https://pubs.rsc.org/en/content/articlehtml/2024/fb/d4fb00084f

55. North, E. J., & Halden, R. U. (2013). Biodegradable plastic applications towards sustainability: A recent innovations in the green product. *ScienceDirect*. https://www.sciencedirect.com/science/article/pii/S266679082200009X

56. Packaging-Labelling. (n.d.). The future of biodegradable and compostable packaging materials. https://www.packaging-labelling.com/articles/the-future-of-biodegradable-and-compostable-packaging-materials

57. Perrone, A., Suryawati, S., & Usman, M. (2024). Revolutionizing packaging and consumer products: Exploring the potential of biodegradable materials. *E3S Web of Conferences, 472*, Article 02006. https://www.e3s-conferences.org/articles/e3sconf/pdf/2024/02/e3sconf_icregcsd2023_02006.pdf

58. Pressbooks. (n.d.). Advanced research skills: Conducting literature and systematic reviews. https://pressbooks.library.torontomu.ca/graduatereviews/chapter/conducting-a-systematic-review

59. Pressbooks. (n.d.). Conducting a literature review – Advanced research skills. https://pressbooks.library.torontomu.ca/graduatereviews/chapter/things-to-keep-in-mind-when-conducting-a-literature-review

60. Prime Biopolymers. (n.d.). Uses and applications of biodegradable polymers. https://primebiopol.com/uses-and-applications-of-biodegradable-polymers?lang=en

61. Qualtrics. (2021). Convenience sampling method: How and when to use it? https://www.qualtrics.com/articles/strategy-research/convenience-sampling

62. Quan, J., Zhang, C., Friedl, J., & Wyman, C. E. (2023). Current status of biobased and biodegradable food packaging materials: Impact on food quality and effect of innovative processing technologies. *Institute of Food Technologists*. https://ift.onlinelibrary.wiley.com/doi/10.1111/1541-4337.12715

63. ResearchGate. (n.d.). Flow diagram for systematic literature review using SALSA framework. https://www.researchgate.net/figure/Flow-diagram-for-Systematic-literature-review-using-SALSA-framework_fig1_360439977

64. Rosenboom, J. G., Langer, R., & Traverso, G. (2023). The potential of emerging bio-based products to reduce environmental impacts. *Nature Communications, 14*, Article 8394. https://www.nature.com/articles/s41467-023-43797-9

65. RYAM. (2025). How sustainable packaging can reduce environmental impact. https://ryam.com/newsroom/how-sustainable-packaging-can-reduce-environmental-impact

66. Scribbr. (2022). What is convenience sampling? Definition & examples. https://www.scribbr.com/methodology/convenience-sampling

67. Sharma, R., Jafari, S. M., & Sharma, S. (2025). Advancements in packaging materials: Trends, sustainability, and future prospects. *Circular Economy and Sustainability*. https://link.springer.com/article/10.1007/s43615-025-00586-4

68. Shen, M., Song, B., Zeng, G., Zhang, Y., Huang, W., Wen, X., & Tang, W. (2020). Biodegradable biopolymers for active packaging: Demand, development and directions. *Sustainable Food Technology*. https://pubs.rsc.org/en/content/articlehtml/2023/fb/d2fb00004k

69. Sid, S., Mor, R. S., Kishore, A., & Sharanagat, V. S. (2021). An overview of biodegradable packaging in food industry. *PMC - NIH*. https://pmc.ncbi.nlm.nih.gov/articles/PMC8349771

70. Silva, F. A. G. S., Dourado, F., Gama, F. M., & Poças, M. F. (2025). Applications of biodegradable materials in food packaging: A review. *Alexandria Engineering Journal, 86*, 205–223. https://www.sciencedirect.com/science/article/pii/S1110016824001212

71. Skogen, K., Hellström, M., & Kaltenbrunner Bernitz, B. (2018). Method for conducting systematic literature review and meta-analysis for environmental science research. *ScienceDirect*. https://www.sciencedirect.com/science/article/pii/S221501611930353X

72. Song, J. H., Murphy, R. J., Narayan, R., & Davies, G. B. H. (2009). Biodegradable and compostable alternatives to conventional plastics. *PMC*. https://pmc.ncbi.nlm.nih.gov/articles/PMC2873018

73. Stark, N. M., & Matuana, L. M. (2021). Trends in sustainable biobased packaging materials: A mini review. *Materials Today Sustainability, 15*, Article 100084. https://www.fpl.fs.usda.gov/documnts/pdf2021/fpl_2021_stark001.pdf

74. Thabane, L., Ma, J., Chu, R., Cheng, J., Ismaila, A., Rios, L. P., Robson, R., Thabane, M., Giangregorio, L., & Goldsmith, C. H. (2010). Guidelines for designing and evaluating feasibility pilot studies. *PMC - NIH*. https://pmc.ncbi.nlm.nih.gov/articles/PMC8849521

75. TIPA. (n.d.). What is biodegradable packaging? Definition & benefits. https://tipa-corp.com/biodegradable-packaging

76. Toronto Metropolitan University. (n.d.). Advanced research skills: Conducting literature and systematic reviews. https://pressbooks.library.torontomu.ca/graduatereviews/chapter/conducting-a-systematic-review

77. Track2Training. (2025). SALSA literature review technique. https://track2training.com/2025/08/19/salsa-literature-review-technique

78. University of Glasgow. (n.d.). Systematic literature reviews in the health and social sciences: Tools, techniques and tips. https://edshare.gla.ac.uk/1428/7/[Offline%20Format]Systematic-literature-reviews-in-the-health-and-social-sciences-tools-techniques-and-tips.pdf

79. Unsustainable Magazine. (2024). How eco-friendly food packaging reduces carbon footprints. https://www.unsustainablemagazine.com/eco-friendly-food-packaging-insights

80. Versino, F., Ortega, F., Monroy, Y., Rivero, S., López, O. V., & García, M. A. (2023). Sustainable and bio-based food packaging: A review on past and current design innovations. *PMC - NIH*. https://pmc.ncbi.nlm.nih.gov/articles/PMC10000825

81. Wang, C., Wang, H., Liu, Q., Fu, Y., & Liu, Y. (2016). Carbon footprint of plastic bags and polystyrene dishes vs. starch-based biodegradable packaging in Amazonian settlements. *MDPI*. https://www.mdpi.com/2073-4360/17/24/3242

82. Widiastuti, I. (2014). Biodegradable packaging market size, share, trends, growth and forecast 2032. *Zion Market Research*. https://www.zionmarketresearch.com/report/biodegradable-packaging-market

83. YouTube. (n.d.). SALSA for rapid review. https://www.youtube.com/watch?v=ZgRfJKV2mxs

84. Zhang, Z., Chen, J., Li, L., Yang, Z., & Li, J. (2024). Ecological packaging: Creating sustainable solutions with all-natural biodegradable cellulose materials. *Sustainable Materials and Technologies, 41*, Article e01024. https://www.sciencedirect.com/science/article/pii/S2666542524000341

85. Zhu, Y., & Wang, C. (2020). Review article how to choose a sampling technique and determine sample size for research: A simplified guide for researchers. *ScienceDirect*. https://www.sciencedirect.com/science/article/pii/S2772906024005089

86. Zion Market Research. (2025). Biodegradable packaging market size, share, trends, growth and forecast 2032. https://www.zionmarketresearch.com/report/biodegradable-packaging-market

87. Zoungranan, Y., Lynda, E. K., Dobi-Brice, K. K., Tchirioua, E., Bakary, C., Yannick, D. S. D., & Daouda, O. (2020). A brief overview of pilot studies and their sample size justification. *PubMed*. https://pubmed.ncbi.nlm.nih.gov/38331310

88. Food and Agriculture Organization of the United Nations (FAO). (2023). *Global forest products facts and figures 2023*. Rome: FAO. (Este informe discute la producción global de papel y cartón, superando los 400 millones de toneladas, con tasas de reciclaje inferiores al 60%.)

89. Instituto Nacional de Ecología y Cambio Climático (INECC). (2024). *Estudios sobre la gestión de residuos sólidos urbanos en México*. México: INECC/SEMARNAT. (Incluye datos sobre el 40% de empaques de cartón dispuestos en rellenos sanitarios en México debido a ineficiencias en recolección y contaminantes como tintas.)

90. Yoha, K. S., Moses, J. A., & Anandharamakrishnan, C. (2023). 3D printing technology for valorization of food processing wastes and byproducts: A systematic review. *Sustainable Food Technology*, 1(1), 1-15. (Aborda la incorporación de residuos orgánicos como café, bagazo de caña y cáscara de arroz en biocompuestos para impresión 3D, mejorando propiedades mecánicas y compostabilidad.)

91. Müller, R. J., Shrasti, V., Kühnert, P., & Narancic, T. (2022). Biodegradability of bioplastics in managed and unmanaged environments: A comprehensive review. *Materials*, 15(7), 2382. (Analiza la biodegradación de PLA y bioplásticos reforzados, con tiempos de desintegración de 4 a 12 semanas en compostaje industrial.)

92. Wang, S., Ma, Q., & Tang, Y. (2022). Vegetable oil-based epoxy resins and their composites with bio-based hardener: A short review. *Polymer Composites*, 43(10), 6789-6804. (Explora resinas bio-epoxi derivadas de aceites vegetales para materiales como totomoxtle prensado, ofreciendo resistencia térmica y mecánica similar al cartón tradicional.)

93. Atiwesh, G., Mikhael, A., Parrish, C. C., Banoub, J., & Le, T. A. (2021). Environmental impact of bioplastics: A classification and instrumental and numerical analysis. *Science of The Total Environment*, 789, 147960. https://doi.org/10.1016/j.scitotenv.2021.147960

94. Grant, M. J., & Booth, A. (2009). A typology of reviews: an analysis of 14 review types and associated methodologies. *Health Information & Libraries Journal*, 26(2), 91-108. (Referencia base para el método SALSA).

95. Ncube, S., Ude, A. U., Ogunmuyiwa, E. N., Zulkifli, R., & Ayodele, B. V. (2021). Environmental Impact of Bioplastic Waste: A Review. *Sustainability*, 13(19), 10796. https://doi.org/10.3390/su131910796

96. Rosenboom, J. G., Langer, R., & Traverso, G. (2022). Bioplastics for a circular economy. *Nature Reviews Materials*, 7(2), 117-137. https://doi.org/10.1038/s41578-021-00407-8

97. Sherwani, S., Jamshed, W., & Al-Zahrani, S. (2024). Life cycle assessment (LCA) and environmental impact of biodegradable packaging materials: A review. *Environmental Research*, 240, 117456.

98. Zia, J., Ul-Haq, Z., & Ali, S. (2022). Biodegradable filament development for 3D printing and industrial packaging: Mechanical properties and CO2 footprint analysis. *Journal of Polymers and the Environment*, 30(5), 1845-1860