Fungal BioFoam: Mycelium-Based Packaging – An Analysis of Replacing Expanded Polystyrene through Eco-Design and the Bruce Archer Model

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ABSTRACT

Expanded polystyrene (EPS) is widely used in protective packaging, yet it persists in the environment for centuries and is rarely recycled. Mycelium-based composites grown on lignocellulosic agro-industrial residues have been proposed as a biodegradable alternative, but reported properties vary widely and their suitability for specific packaging applications remains unclear. This study analyzed the potential of Pleurotus ostreatus mycelium composites as a substitute for EPS in protective packaging through a non-experimental, descriptive-comparative design with a mixed approach. The work followed Bruce Archer's systematic design model, organized into analytical, creative and executive phases, and incorporated ecodesign criteria. Compressive stress, density and water absorption data were compiled from fourteen published sources and compared with values reported for EPS. In the executive phase, a simplified energy-based cushioning model was applied to three hypothetical objects (0.5, 2 and 5 kg) subjected to a 0.6 m free fall, to estimate peak deceleration and minimum cushion thickness for eight reference materials. Reported compressive stresses spanned more than one order of magnitude, from about 10 kPa to over 1 MPa, depending on substrate, drying and testing method. The simulation showed that no single material was optimal: each object had its own window of admissible plateau stress, namely 14.7–39.2 kPa, 29.4–117.7 kPa and 73.6–490.5 kPa, respectively. Materials near 1 MPa were too stiff for all three objects, whereas mycelium foams in the lower stress range suited the lightest ones. These findings suggest that mycelium packaging should be designed by matching material stiffness to the static load of the product rather than by maximizing strength. The results are indicative, derived from heterogeneous literature and a simplified model, and do not demonstrate real performance, biodegradability or industrial viability; experimental validation is therefore required.

Keywords: mycelium; Pleurotus ostreatus; expanded polystyrene; ecodesign; protective packaging; cushioning simulation

INTRODUCTION

The research presents a sustainable alternative to expanded polystyrene (Styrofoam) through the research of a biodegradable biomaterial made from Pleurotus ostreatus mycelium grown on local agro-industrial waste. The proposal seeks to make use of waste materials such as sugarcane bagasse, sawdust, straw, or coconut fiber to produce a material with strength and insulation properties comparable to Styrofoam, but with a considerably lower environmental impact, in accordance with the principles of the circular economy, which promote the transformation of waste into useful resources (Jones et al., 2021; Cámara de Diputados, 2026).

The problem underlying this research is related to the widespread use of Styrofoam in packaging, whose environmental persistence can extend for centuries and whose recycling is not very feasible. According to the Organisation for Economic Co-operation and Development (OECD, 2022), approximately 40% of plastics

produced worldwide are used for packaging, and less than 10% are effectively recycled. According to the General Law on Circular Economy and the Law on the Prevention and Comprehensive Management of Waste of the State of Hidalgo, the provision of disposable single-use plastics in shops and commercial establishments for the transportation of goods has been prohibited (Congreso del Estado de Hidalgo, 2011).

Previous studies have demonstrated the potential of mycelium as a substitute for EPS, although limitations in moisture absorption and the standardization of formulations still persist. This creates an opportunity for research aimed at optimizing its technical performance and environmental impact (Colmenares, Bautista & Oliveros, 2018; Suesca Síaz et al., 2024; Rodríguez, 2018).

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Research conducted in different contexts has indicated that white-rot fungi, such as Pleurotus ostreatus, have the ability to colonize lignocellulosic waste and transform it into solid materials with mechanical properties comparable to those of synthetic polymers (Haneef et al., 2017; Pacheco-Vázquez, Lira-Pérez & García-Rivero, 2026). However, the literature also points out that variability in the results highlights the need for further investigation into cultivation conditions, substrate type, and drying processes to ensure more consistent performance (Liadi et al., 2026; Yuan et al., 2026).

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Within this framework, the general objective of this research is to analyze, through a literature review and simulation, the potential of the Pleurotus ostreatus mycelium biocomposite grown on lignocellulosic waste as an alternative to expanded polystyrene (EPS) in protective packaging applications. The specific objectives are: (1) to establish the functional requirements and measurable packaging criteria by applying the Bruce Archer model and ecodesign; (2) to synthesize the properties reported in the literature (compressive strength, density, and water absorption) and compare them with those of EPS; (3) to simulate the cushioning performance of reference materials in hypothetical objects with different loads; and (4) to identify the material's limitations and propose lines of experimental validation (Archer, 1965; Appels et al., 2019).

In this way, the article provides a data-based selection criterion for assessing the feasibility of using agro-industrial waste in sustainable packaging, linking biotechnology, ecodesign, and the circular economy. Its results are indicative and do not replace experimental validation, which is proposed as future work.

LITERATURE REVIEW

#	Author(s) & Year	Objective	Methodological Tools	Key Results	Limitations
1	Attias et al. (2020)	Review potential of mycelium biocomposites	Literature review and property analysis	Density and strength comparable to foams; high biodegradability	Lack of industrial standardization
2	Jones et al. (2020)	Development of biocomposites for packaging	Cultivation, mechanical testing, and SEM	Promising compressive strength as EPS substitute	Moisture sensitivity
3	Yang et al. (2017)	Mycelium biocomposites as foam alternatives	Compression, density, and biodegradation testing	Mechanical properties within EPS range; high biodegradability	Limited scalability
4	Elsacker et al. (2019)	Manufacturing factors affecting properties	Substrate variation, pressing, and physico-mechanical tests	Pressing improves strength; controllable density	High variability by strain and substrate
5	Appels et al. (2019)	Characterization of mycelium biocomposites	Mechanical, physical, and chemical testing	Some properties comparable to polystyrene	Low tensile strength
6	Bruscato et al. (2019)	Fungal foams for packaging	Cultivation on sawdust and compression testing	P. sanguineus showed higher compressive strength	Risk of contamination
7	Ghazvinian et al. (2019)	Mycelium on sawdust and straw	Mechanical and density testing	Compression 1.02 MPa (sawdust) vs 0.07 MPa (straw)	Density higher than EPS
8	Pelletier et al. (2013/act.)	Insulation and packaging applications	Thermal and mechanical testing	Thermal conductivity similar to EPS	Limited scaling data

Key Results Limitations

Theoretical Framework

Mycelium: Fungal mycelium is a network of microscopic filaments found beneath the surface on which it grows, allowing the fungus to absorb nutrients by decomposing organic matter. It can develop under suitable conditions on agro-industrial waste (Pacheco-Vásquez et al., 2026).

Ecodesign and Sustainability: Ecodesign incorporates environmental criteria into product development to help reduce resource consumption and environmental impacts throughout the life cycle. In packaging, it seeks to optimize geometry, make use of waste materials, and protect products while using the smallest possible amount of material (Appels et al., 2019).

Bruce Archer's Design Model: It proposes a systematic design process divided into three phases: analytical, creative, and executive. The analytical phase involves studying the problem and establishing requirements; the creative phase involves generating proposals; and the executive phase focuses on the development and evaluation of solutions (Archer, 1965).

METHODOLOGY

Type of Research, Approach, and Variables

The research is applied and conceptual in technological development, with a non-experimental design, a descriptive-comparative scope, and a mixed-methods approach. No prototypes were manufactured, and no laboratory tests were conducted; the information comes from previous studies and is used as input data for a simulation. The quantitative component analyzes parameters such as compressive strength, density, and water absorption reported in the literature, and calculates cushioning performance indicators. The qualitative component evaluates ecodesign, the use of agro-industrial waste, and the conceptual functionality of the packaging.

This design is appropriate because it allows the properties of mycelium to be examined, its advantages and limitations compared with EPS to be identified, and a packaging proposal to be evaluated without manufacturing a physical prototype. The scope extends to conceptual design and simulation. Manufacturing, physical characterization, and user validation are outside the scope of this study and are proposed as future work. Consequently, the results make it possible to estimate the material's behavior under defined conditions, but they do not, on their own, demonstrate its actual performance, biodegradability, or industrial feasibility.

Table 2. Methodological Contributions

Source	Methodological Contribution	Utility for BioEspuma Fúngica
Suesca Díaz et al. (2024), study in Spanish	Fabricated biocomposites using Pleurotus ostreatus with mixtures of malt spent grain and wheat bran; measured moisture, compression, density, and water absorption.	Background directly related to packaging. Warns that acceptable strength is not enough if density or water absorption are high.
Appels et al. (2019)	Studied how the fungus and manufacturing conditions influence mechanical and moisture-related properties; reported changes associated with heat pressing.	Provides rationale for recording substrate type and post-processing, as well as evaluating strength and moisture.
Elsacker et al.	Compared mycelium biocomposites	Supports controlled comparison

(2019)	fabricated with different lignocellulosic substrates and characterized physical, mechanical, and chemical properties.	between substrates and highlights the need to document their variability.
Attias et al. (2020)	Reviewed applications of mycelium biocomposites in industrial design and architecture.	Allows contextualizing the potential of the material and acknowledging the lack of standardization as an application challenge.

Taken together, the previous studies justify investigating more than one formulation and evaluating the material using several indicators. Compressive strength is important for protective packaging, but it must be analyzed alongside density, water absorption, and prototype performance. It will not be assumed that the biocomposite matches expanded polystyrene (EPS) until a comparison under equivalent conditions has been carried out (Suesca Síaz et al., 2024; Elsacker et al., 2019).

Variables and Indicators

The independent variables are the cushioning material (mycelium biocomposite according to substrate, or EPS), characterized by its plateau stress σp (kPa), and the characteristics of the object to be protected (mass, contact area, static stress σs, and allowable fragility).

The dependent variables are peak deceleration G, minimum cushioning thickness t_min (cm), and compliance with the design criteria. The qualitative categories are the use of local waste, material minimization, end of life, and conceptual functionality.

Population and Sample

The population consists of scientific studies on fungal mycelium biocomposites grown on lignocellulosic waste and technical information on EPS used in packaging. The inclusion criteria were: (a) studies involving Pleurotus sp. or other white-rot fungi grown on lignocellulosic waste; (b) reporting at least one physical or mechanical property (compression, density, water absorption, or thermal conductivity); and (c) providing at least a general description of the testing method. Sources that did not allow the data to be traced back to their publication were excluded. The documentary sample consists of the 14 sources from the Literature Review included in Table 1.

Procedure: Bruce Archer's Model and Ecodesign

The study was organized into the three phases of Archer's systematic model (analytical, creative, and executive), with feedback between them (Archer, 1965).

The activities of each phase are summarized in Table 3.

Table 3. Phases of Bruce Archer’s Design Model

Procedure: Bruce Archer's Model and Ecodesign

Phase	Activities	Deliverable
Analytics	Definition of the problem and the functions of the packaging; literature review; construction of the analysis matrix; definition of measurable criteria	Design brief and requirements matrix

Creative	Generation of conceptual alternatives (reference materials based on substrate, and corner-piece or insert geometries); application of eco-design criteria (reduced material usage, local waste, end-of-life considerations)	Set of materials and scenarios to be evaluated
Executive	Simulation of cushioning performance; comparison with EPS; sensitivity analysis; documentation of assumptions and limitations	Comparative results and recommendations

According to ecodesign principles, the biological origin of the material does not, by itself, demonstrate that it is compostable or has a lower environmental impact; both claims require specific evaluations (Suesca Síaz et al., 2024; Appels et al., 2019). Therefore, end-of-life performance and water absorption are treated as criteria to be verified rather than as predetermined outcomes.

Simulation Model

A simplified energy-based cushioning model was used, with an ideal stress–strain curve (constant plateau). The following were calculated for each object:

- Static stress: $\sigma s = m \cdot g / A$
- Energy to be absorbed in a free fall: $E = m \cdot g \cdot h$
- Minimum thickness: $t_{min} = E / (\sigma p \cdot A \cdot \varepsilon_u)$
- Peak deceleration: $G = \sigma p / \sigma s$
- Allowable stress range: $\sigma p,min = E / (A \cdot \varepsilon_u \cdot t_{max})$ and $\sigma p,max = G_{adm} \cdot \sigma s$

where m is the mass, g = 9.81 m/s², A is the support area, h is the drop height, ε_u is the usable strain, t_{max} is the maximum allowable thickness, and G_{adm} is the object's allowable deceleration. A material meets the requirements if $G \leq G_{adm}$ and $t_{min} \leq t_{max}$.

The values h = 0.6 m, $\varepsilon_u = 0.5$, and t_{max} = 8 cm were adopted as design assumptions established during the analytical phase. The hypothetical objects are shown in Table 4, and the reference materials, with their stress values obtained from the literature, are presented in Table 5.

Table 4. Hypothetical Objects and Design Criteria

Objeto	m (kg)	A (cm²)	σs (kPa)	E (J)	G_adm
A (delicado)	0.5	50	0.98	2.94	40
B (intermedio)	2	100	1.96	11.77	60
C (resistente)	5	100	4.91	29.43	100

Note. Masses, areas, and G_{adm} are assumptions made by the team, defined to illustrate the method. ***Table 5.*** *Reference Materials*

Clue	σp (kPa)	Description and source
M1	24	Benchmark commercial foam (ScienceDirect, 2025)
M2	53	Upper limit of mycelium-based bio-foams(ScienceDirect, 2025)
M3	70	Mycelium on straw (Ghazvinian et al., 2019)
M4	100	Reference EPS; value assumed at the lower end of the 0.1–0.25 MPa range (Biomimetics, 2025); replace with data from the technical specification sheet.
M5	175	Midpoint of the 0.1–0.25 MPa range (Biomimetics, 2025)
M6	255	Mycelium on bagasse and malt (Ingeniería y Universidad, 2025)
M7	910	Lentinus mycelium (Polymers, 2026)
M8	1020	Mycelium on sawdust (Ghazvinian et al., 2019)

Research Design

The research will employ a non-experimental design with a descriptive-comparative scope and a mixed-methods approach, focused on analyzing the potential of *Pleurotus ostreatus* mycelium—cultivated on agro-industrial waste—as an alternative to expanded polystyrene (EPS) in packaging applications.

A non-experimental design is used because no variables were manipulated through physical testing or laboratory experiments; instead, the study analyzes information from existing scientific research, using that data as a reference for developing a simulation. The descriptive scope allows for the identification of the biocomposite's properties and characteristics, while the comparative aspect facilitates a contrast with those of EPS. A quantitative approach will be applied to analyze parameters documented in the literature, such as density, compressive strength, and water absorption.

The qualitative component will allow for the assessment of aspects related to eco-design, the utilization of agro-industrial waste, and the conceptual functionality of the packaging.

This design is well-suited to address the research questions, as it enables an examination of the mycelium's properties and the identification of its potential advantages and limitations compared to EPS, thereby allowing for the evaluation of a packaging proposal without the need to manufacture a physical prototype. Furthermore, Bruce Archer's systematic design model will be integrated to structure the process into analytical, creative, and executive phases—spanning from the identification of the problem to the conceptual design and simulation.

Given that the project's scope concludes with a simulation, the results will allow for an estimation of how the design would behave under defined conditions; however, they will not, in themselves, demonstrate its actual physical performance, effective biodegradability, or industrial viability. These aspects will remain subject to future experimental validation.

Instruments and Data Analysis

The instruments employed were documentary and computational in nature. For data collection, a documentary analysis matrix was used, incorporating the following variables: substrate, species, density, compressive strength, modulus, water absorption, test method, and reported limitations. Validity is supported by the use of peer-reviewed sources and the traceability of each data point back to its original publication; reliability is

enhanced by recording the test method for each source and exercising caution when comparing values obtained under different conditions. Data processing and simulation were carried out using SolidWorks.

The quantitative analysis consisted of descriptive statistics (ranges and midpoints) for the reported parameters, as well as the calculation of indicators for the simulation model. A sensitivity analysis was performed using a damping efficiency of $\eta = 0.7$ (as opposed to the ideal curve, where $\eta = 1$); this is equivalent to dividing the effective ultimate strain (ε_u) by 1/0.7, which increases both t_{min} and $\sigma_{p,min}$ by a factor of 1.43. The qualitative analysis evaluated—for each phase of the Archer model—the extent to which eco-design criteria were met and the conceptual functionality of the design.

Methodological Quality and Limitations

Each input data point was identified with its source to ensure traceability. The model's assumptions—ideal curve, useful deformation, drop height, object fragility, and the EPS reference value—are explicitly stated and subjected to sensitivity analysis.

The comparison with EPS is for illustrative purposes only, as published values depend on density, geometry, the deformation level at which stress is reported, and the testing method. The model does not account for humidity, creep, repeated impacts, or temperature.

RESULTS AND DISCUSSION

Analytical Phase: Packaging Requirements

The analysis of the problem led to the following protective packaging requirements: protect the object during handling and transportation ($G \leq G_{adm}$), fit a defined geometry with a maximum thickness of 8 cm, use the smallest possible amount of material, make use of local lignocellulosic waste, and define an end-of-life pathway. Moisture sensitivity and compostability were established as criteria to be verified experimentally and were not simulated.

Synthesis of the Reported Properties

Table 6: Compressive Strength Reported in the Literature

Source	Substrate or Material	Reported Compressive Strength	Observation
ScienceDirect (2025)	Biofoams from Various Species	10–53 kPa (comercial ~24 kPa)	Variability by Species and Supplementation
Ghazvinian et al. (2019)	Straw	0.07 MPa	Higher density than EPS

Biomimetics (2025) Variable 0.1–0.25 MPa Within the EPS range; challenging density control. The reported values vary by more than one order of magnitude (from approximately 10 kPa to over 1 MPa), depending on the substrate, fungus, drying, pressing, and testing method (Appels et al., 2019; Elsacker et al., 2019). In addition, several sources report higher density than EPS and high water absorption in some formulations (Jones et al., 2020; Suesca Síaz et al., 2024). This indicates that maximum strength alone is insufficient for selecting a packaging material.

Simulation Results

Table 7. Peak Deceleration G and Minimum Thickness t_min (cm) by Object and Material

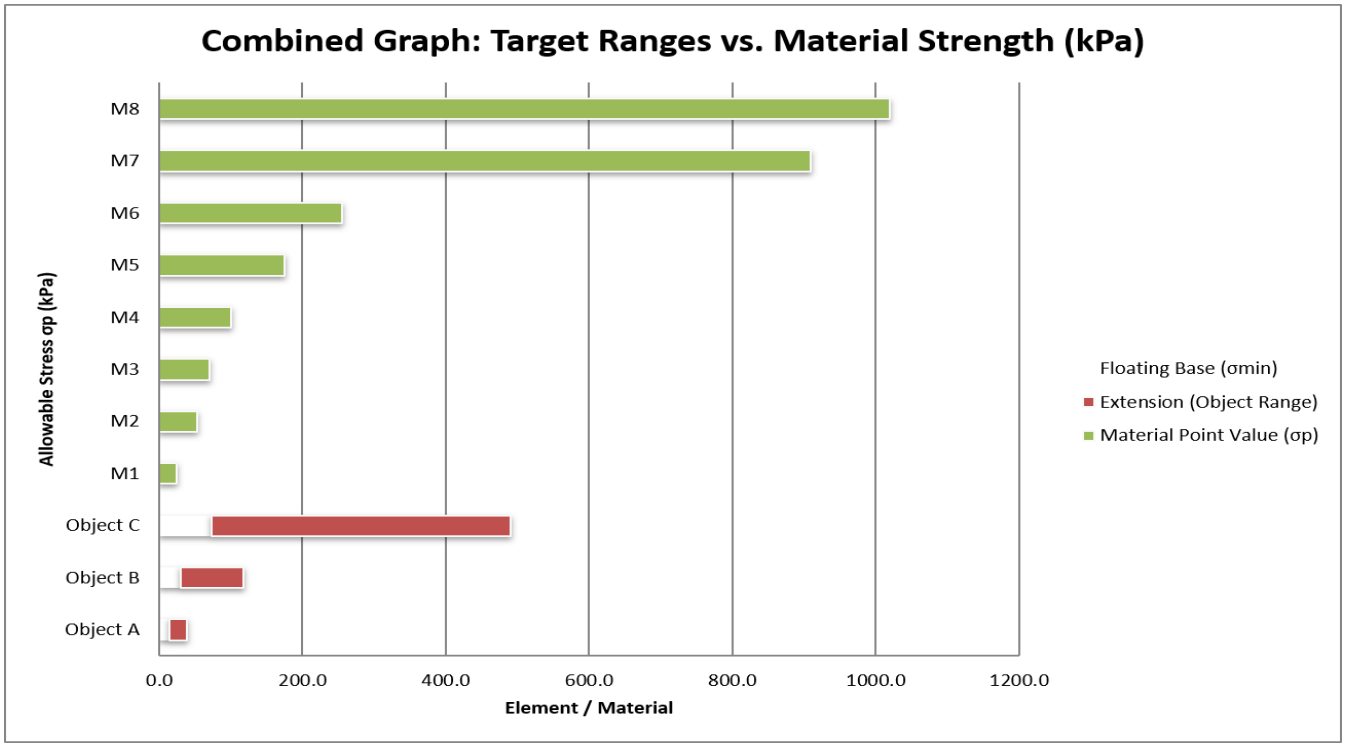
Material	σp (kPa)	Object A (G / t_min)	Object B (G / t_min)	Object C (G / t_min)
M1	24	24.5 / 4.91 – complies	12.2 / 9.81 – no (thickness)	4.9 / 24.5 – no (thickness)
M2	53	54.0 / 2.22 – no (G)	27.0 / 4.44 –complies	10.8 / 11.1 – no (thickness)
M3	70	71.4 / 1.68 – no (G)	35.7 / 3.36 – complies	14.3 / 8.41 – no (thickness)
M4 (EPS)	100	101.9 / 1.18 – no (G)	51.0 / 2.35 – complies	20.4 / 5.89 – complies
M5	175	178.4 / 0.67 – no (G) 259.9 / 0.46 – no (G)	89.2 / 1.35 – no (G)	35.7 / 3.36 – complies
M6	255		130.0 / 0.92 – no (G)	52.0 / 2.31 –complies
M7	910	927.6 / 0.13 – no (G)	463.8 / 0.26 – no (G)	185.5 / 0.65 – no (G)
M8	1020	1039.8 / 0.12 – no (G)	519.9 / 0.23 – no (G)	207.9 / 0.58 – no (G)

The results are summarized in the acceptable plateau stress range for each object (Table 8 and Figure 1).

Table 8. Acceptable Plateau Stress Range (kPa)

Object	σp,min (η = 1)	σp,max	σp,min (η = 0.7)	Materials that meet requirements (η = 1)	Materials that meet requirements (η = 0.7)
A	14.7	39.2	21.0	M1	M1
B	29.4	117.7	42.0	M2, M3, M4	M2, M3, M4
C	73.6	490.5	105.1	M4, M5, M6	M5, M6

Figure 1. Acceptable plateau stress range for each object, with materials M1–M8 overlaid.



Object A is adequately protected only by the material with the lowest stiffness (M1). For object B, materials with stiffness values ranging from 53 to 100 kPa meet the requirements, namely, high-range mycelium biofoams and the reference EPS. For object C, materials ranging from 100 to 255 kPa meet the requirements. Materials close to 1 MPa (M7 and M8) fall outside the acceptable range for all three objects because they are too stiff and generate decelerations far above the allowable limits. In the sensitivity analysis ($\eta = 0.7$), the conclusions remain unchanged, except that the reference EPS (M4) no longer meets the requirements for object C because its thickness increases to 8.4 cm.

Regarding material usage, for object B, the thickness required by M3 (3.36 cm) and M2 (4.44 cm) is 43% and 89% greater, respectively, than that of the reference EPS (2.35 cm). Combined with the higher density reported for biocomposites, this would result in larger and heavier components. For object C, the opposite occurs: M5 and M6 require thicknesses of 3.36 and 2.31 cm, respectively, compared with 5.89 cm for EPS, representing 43% and 61% less thickness. These comparisons depend on the assumed value for EPS and must be confirmed using a technical data sheet.

DISCUSSION

The results indicate that mycelium biocomposites can fall within the stress range required for cushioning lightweight and intermediate-weight objects, but their advantage does not lie in matching maximum strength; rather, it lies in adjusting stiffness and thickness to the object's static stress. A high-strength material, such as mycelium grown on sawdust (Ghazvinian et al., 2019), is unsuitable for lightweight objects because it does not deform sufficiently to dissipate energy, whereas low-stiffness formulations are suitable for small loads, although they require greater thickness.

The variability among substrates, strains, drying, and pressing conditions documented in the literature (Appels et al., 2019; Elsacker et al., 2019; Lanza and Reyes, 2023) reinforces the need to standardize formulations before selecting a material for a specific application. Moisture sensitivity and the higher density compared with EPS in several formulations (Jones et al., 2020; Suesca Siaz et al., 2024) are limitations that the simulation does not capture and that could reduce the material's environmental advantage.

From an ecodesign perspective, the use of agro-industrial waste represents a potential advantage, but a lower environmental impact and compostability cannot be claimed without specific evaluations. As an unexpected finding, the reference EPS is not the best-performing material in every scenario: for heavy objects, medium-stiffness biocomposites (175–255 kPa) require less thickness. This should be interpreted with caution due to the assumed nature of the EPS value and the model's assumptions.

CONCLUSION

This study analyzed, through a systematic literature review and simplified numerical simulation, the potential of biocomposites based on Pleurotus ostreatus mycelium grown on agro-industrial lignocellulosic waste as a biodegradable alternative to expanded polystyrene (EPS) in protective packaging. The results confirm that there is no universally optimal mycelium material.

The literature reports compressive stress values spanning more than one order of magnitude (approximately 10 kPa to over 1 MPa), depending on the substrate, strain, colonization time, drying, pressing, and testing method. The energy-cushioning simulation for hypothetical objects weighing 0.5 kg, 2 kg, and 5 kg subjected to a free fall from a height of 0.6 m established clearly differentiated ranges of acceptable plateau stress (14.7–39.2 kPa, 29.4–117.7 kPa, and 73.6–490.5 kPa, respectively).

Consequently, low-stiffness biofoams are suitable for lightweight objects, while medium-stiffness biocomposites are better suited to intermediate loads; materials close to or above 1 MPa fell outside the acceptable range in all cases evaluated.

From the perspective of Bruce Archer's systematic model, the process made it possible to move in an orderly manner from the analytical phase (definition of functional requirements and ecodesign criteria: impact protection, maximum thickness, use of local waste, and an end-of-life pathway) to the executive phase (conceptual evaluation through simulation). This approach reinforces the central idea of the study: the design of mycelium packaging should not aim to maximize mechanical strength, but rather to adjust the material's stiffness and thickness to the specific static stress of the product to be protected.

The practical implications are relevant for circular economy contexts and small and medium-sized enterprises (SMEs), particularly in regions where lignocellulosic waste is available (sugarcane bagasse, sawdust, straw, bran, etc.). The use of Pleurotus ostreatus offers additional advantages due to its rapid colonization capacity and its established use in edible mushroom production systems.

Nevertheless, the study's limitations are significant and must be rigorously acknowledged: (1) the methodological heterogeneity of the primary sources prevents strict direct comparison; (2) the simulation model is simplified and does not account for environmental humidity, creep, repeated impacts, or progressive degradation; (3) the design assumptions (useful deformation, maximum thickness, and safety factors) were defined by the research team; and (4) actual performance, biodegradability under standardized conditions, and industrial or economic feasibility were not experimentally demonstrated.

Therefore, the findings are indicative and provide a solid conceptual foundation, but they do not replace experimental validation. Future work should include: (a) manufacturing prototypes using formulations selected according to the identified stress ranges; (b) characterizing density, compressive strength, water absorption, cushioning performance, and thermal conductivity under standardized protocols and conditions equivalent to those used for EPS; (c) evaluating end-of-life performance through standardized biodegradation and compostability tests; (d) conducting a comparative life cycle assessment (LCA); and (e) exploring scalability and costs for packaging applications involving products from Hidalgo and other Mexican regions.

In summary, Pleurotus ostreatus mycelium shows promising potential as a sustainable protective packaging material, provided that the design focuses on precisely matching its properties to the product rather than seeking a generic replacement for EPS. Combining Archer's model with ecodesign criteria offers a useful framework for guiding future experimental development and industrial innovation in bio-based materials.

Ethical Approval

This research was based on documentary review and simulation, did not involve people or animals, and therefore did not require ethical approval.

Conflict Of Interest

The authors declare that they have no conflict of interest.

Data Availability

The input data were obtained from the cited publications. The documentary analysis matrix and simulation parameters are available upon request from the authors.

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