CITRUS-BASED BIOPLASTICS FOR THERMAL AND ACOUSTIC INSULATION AT AN INTERMODAL STATION

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THIS RESEARCH ADDRESSES ENVIRONMENTAL POLLUTION LINKED TO CONSTRUCTION AND INADEQUATE THERMAL AND ACOUSTIC INSULATION IN HIGH-TRAFFIC URBAN AREAS, USING THE LA CISTERNA INTERMODAL STATION IN SANTIAGO, CHILE, AS A CASE STUDY. THE OBJECTIVE IS TO DEVELOP AND VALIDATE A BIO-BASED COMPOSITE MATERIAL MADE FROM ORANGE PEELS AND NATURAL BINDERS AS A SUSTAINABLE ALTERNATIVE TO EXPANDED POLYSTYRENE (EPS). THE METHODOLOGY FOCUSES ON EXPERIMENTAL FORMULATION, SPECIMEN FABRICATION, STANDARDIZED PHYSICAL, THERMAL, AND ACOUSTIC CHARACTERIZATION TESTS, AND THE DESIGN OF A MODULAR PROTOTYPE FOR TRAIN PLATFORMS. RESULTS DEMONSTRATE INSULATION PROPERTIES COMPARABLE TO OR BETTER THAN EPS, ALONG WITH ADVANTAGES IN BIODEGRADABILITY, COST, AND PRODUCTION FEASIBILITY USING AGRO-INDUSTRIAL WASTE. THESE FINDINGS ENABLE US TO PROPOSE THIS DESIGN AS A VIABLE SOLUTION FOR SMALL AND MEDIUM-SIZED ENTERPRISES, WHILE FOSTERING COMMUNITY ENGAGEMENT AND POSITIONING THE PROPOSAL AS A PUBLIC POLICY PROJECT TO SECURE GOVERNMENT FUNDING FOR SUSTAINABILITY AND ENTREPRENEURSHIP. THIS WORK IS BASED ON A MASTER'S THESIS AND IS PRESENTED AS A TECHNICALLY AND ENVIRONMENTALLY RELEVANT CONTRIBUTION TO THE CONSTRUCTION INDUSTRY, ALIGNED WITH SUSTAINABLE DEVELOPMENT GOALS 9, 12, AND 13.

KEYWORDS: BIOPLASTIC, SUSTAINABLE CONSTRUCTION, ORANGE PEEL, INDUSTRIAL DESIGN

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INTRODUCTION

The construction industry is one of the sectors with the greatest environmental impact globally, due to its high consumption of natural resources and solid waste generation. In Chile, the industry produces more than 50% of industrial waste, posing urgent sustainability and energy efficiency challenges (Chilean Chamber of Construction, 2022). Alongside this, the growing complexity of urban environments has turned noise pollution into a well-documented environmental and public health issue. According to the World Health Organization, prolonged noise exposure can lead to hearing, cardiovascular, cognitive, and psychological disorders, affecting quality of life (WHO, 2018, 2022). This is particularly critical in high-traffic urban transport infrastructure such as Santiago's La Cisterna Intermodal Station, where noise levels range from 65 to 85 dB—exceeding recommended thresholds and affecting both users and workers (Ministry of the Environment, 2023).

In contemporary construction, expanded polystyrene has become one of the most widely used materials for thermal and acoustic insulation in urban infrastructure. However, its fossil-based origin, low biodegradability, and the environmental impact of its production and disposal pose significant limitations given current sustainability challenges (Prasittisopin et al., 2022).

Given these challenges, exploring alternatives that combine superior insulation properties with a lower ecological footprint is essential. Recovering agro-industrial waste, such as orange peels, offers an innovative strategy. The fibrous, porous structure of this byproduct not only enhances sound absorption but also contributes to thermal insulation, offering potentially superior performance to expanded polystyrene (Hernández-Rodríguez et al., 2026).

This research addresses the lack of sustainable solutions that integrate thermal and acoustic insulation into urban infrastructure while also considering energy efficiency and reducing the environmental impact of materials. Accordingly, we ask: Can a bio-based material made from orange peels offer acoustic and thermal properties superior to those of expanded polystyrene, positioning it as a sustainable alternative for construction?

This study aimed to develop a bio-based composite from orange peel waste and validate its performance as a thermal and acoustic insulator. We defined the manufacturing process, evaluated the material's properties through standardized tests, and designed a modular panel for use at La Cisterna Intermodal Station. Building on a master's thesis, this research contributes to sustainable design and agricultural waste recovery, advancing construction solutions aligned with the Sustainable Development Goals (United Nations, 2021).

Specifically, this study proposes that developing a bio-based material from orange peels—with acoustic and thermal properties superior to those of expanded polystyrene—provides a sustainable construction alternative that addresses several United Nations Sustainable Development Goals (SDGs). It aligns with SDG 12 by promoting the circular economy through agro-industrial waste recovery and reducing fossil-based polymer use. Similarly, it supports SDG 13 by improving building energy efficiency and lowering emissions associated with energy consumption. In terms of innovation, it connects to SDG 9 by advancing new technological solutions for resilient and sustainable infrastructure.

THEORETICAL FRAMEWORK

The construction industry ranks among the sectors with the greatest environmental impact, accounting for over 20% of global solid waste and approximately 56% of Chile's industrial waste (Ministry of the Environment, 2021). Against this backdrop, transitioning to sustainable insulation materials is a critical strategy for mitigating environmental degradation. Recovering agro-industrial waste, such as orange peels, to develop biocomposites offers a viable technical alternative that combines thermal efficiency, acoustic performance, and a low carbon footprint. This approach aligns with the United Nations Sustainable Development Goals (SDGs) (United Nations, 2021), particularly SDG 9 (infrastructure innovation), SDG 12 (responsible production and circular economy), and SDG 13 (climate action).

Contemporary construction must meet rising performance standards for both thermal and acoustic insulation. The World Health Organization identifies noise pollution as a major public health concern, recommending maximum levels of 65 dB during the day and 55 dB at night (WHO, 2018). In Chile, sound pressure levels are regulated by Supreme Decree No. 38/2011 of the Ministry of the Environment, while national standards NCh 2785 and NCh 2786 (2003) establish test methods for evaluating the sound insulation properties of materials.

Energy efficiency requirements for buildings are set by the Energy Rating Regulation for Residential Buildings and NCh 853. Conventional insulation materials such as expanded polystyrene (EPS) offer good thermal performance but poor acoustic insulation; they are also highly polluting, non-biodegradable, and estimated to take up to 500 years to degrade (Carpio Toral, 2018). These limitations underscore the need for alternatives that combine technical performance with sustainability.

Approaches such as industrial ecology and the circular economy propose a transition from linear to circular production models, in which waste from one industry becomes input for another, optimizing material use and reducing waste generation (Asyraf et al., 2022; Ellen MacArthur Foundation, 2013; Huuhka et al., 2020). Industrial ecology rethinks production systems to close material loops, while the circular economy focuses on redesigning processes and products to eliminate waste (Ellen MacArthur Foundation, 2013). Within this framework, agro-industrial waste positions itself as a significant source of raw materials for developing new construction materials.

Among these, citrus waste—particularly orange peel—holds great potential for value-added applications. This byproduct, which can account for 25% to 40% of the fruit's weight (Pathak et al., 2017), contains pectin, cellulose, and hemicellulose—natural polymers with structural and gelling properties that make it suitable for manufacturing bio-based materials (Wu et al., 2018). Its use not only reduces organic waste but also opens new opportunities in sustainable construction.

The citrus agroindustry generates millions of metric tons of waste annually, primarily in the form of peels, which can account for 25% to 40% of the fruit's weight (Pathak et al., 2017). In Chile, national production exceeds 120 million metric tons of fresh fruit per year, of which nearly 25 million metric tons go to the processing industry, resulting in large volumes of organic waste (Layseca Astudillo, 2021).

In this context, the development of biocomposites and bioplastics represents a promising line of research. These materials combine natural polymer matrices with plant-based reinforcements to offer mechanical, thermal, and acoustic properties comparable to those of conventional materials (Baillie & Vanasupa, 2003). Although some biopolymers still face limitations in terms of cost and scalability (Raj et al., 2023), various studies have shown the potential of agricultural waste-derived materials—such as sugarcane fibers, bamboo, and fruit peels—as low-cost, low-impact insulation alternatives (Collivignarelli et al., 2020).

At the intersection of sustainability, waste recovery, and materials innovation, a critical challenge persists: the lack of solutions that integrate thermal performance, sound absorption, and environmental viability in real-world settings. While natural-fiber biocomposites have advanced, a gap remains in experimentally validating specific waste-derived materials and translating them into concrete urban infrastructure applications.

This research lies at the intersection of design, materials science, and sustainability, proposing an orange peel-based biocomposite as a thermal and acoustic insulation alternative. Unlike studies focused solely on material formulation, this work outlines a comprehensive process—from mechanical, thermal, and acoustic characterization to the design and validation of a prototype in a real-world setting. This approach enables us to evaluate the material's performance under controlled conditions and analyze its behavior in a specific urban context, bridging the gap between experimental development and practical implementation in building systems.

METHODOLOGY

The research followed an iterative experimental approach within the Material-Driven Design (MDD) paradigm to ensure traceability, reproducibility, and scientific rigor throughout the process. The methodology was structured sequentially, tracking the material's transformation from raw material sourcing to validation in a real-world setting.

1. SOURCING AND PREPARATION OF RAW MATERIALS

The raw material consisted of orange peels sourced from a juice processing plant to ensure uniformity and a consistent supply. Both the flavedo (outer layer) and the albedo (inner layer) were incorporated, with the latter being the most important structural component due to its high pectin, cellulose, and hemicellulose content.

Samples were collected systematically over a two-week period, yielding representative batches of 100 to 200 kg of fresh peels. Each batch was assigned a unique code, and the collection date, transport conditions, and environmental variables were recorded to monitor potential variations linked to degradation.

The peels were washed with drinking water and disinfected with a diluted hypochlorite solution. They were then air-dried and oven-dried at 60 °C until residual moisture content fell below 10%, as measured by a digital hygrometer.

Once dry, the peels were mechanically ground and sieved to obtain a powder with a controlled particle size (<2 mm). This material was stored in airtight containers with desiccant at controlled room temperature until use. Reducing the particle size increased the specific surface area, which improved cohesion with the binders, facilitated the formation of a continuous matrix, and enhanced the microporosity relevant to thermal and acoustic performance.

2. DEFINITION OF THE MATERIAL SYSTEM

Next, we selected binders based on criteria such as plant-based origin, biodegradability, local availability, chemical compatibility with the shell's polysaccharides, mixture workability, and curing times.

We selected four main binders—cornstarch, reinforced pectin, agar, and glycerin as a plasticizer—and explored both simple and mixed combinations. An initial screening helped rule out formulations with shrinkage, cracking, or brittleness, allowing us to select those with greater dimensional stability and structural cohesion.

No materials with binding properties comparable to orange peel were identified in this study, reinforcing the exploratory nature of this material system.

3. EXPERIMENTAL DESIGN AND TEST SPECIMEN FABRICATION

We developed a factorial experimental design with three independent variables: shell percentage (50%, 60%, 70%, and 80%), binder type (four options), and plasticizer content (0%, 5%, and 10%). This yielded 24 formulations, each replicated three times, for a total of 72 test specimens.

Test specimens were produced in different shapes depending on the test requirements: discs with diameters of 29 and 100 mm for acoustic tests in an impedance tube, plates measuring 300 × 300 × 30 mm for thermal tests, and cubes of 50 × 50 × 30 mm for physical tests.

The manufacturing process consisted of controlled mechanical mixing, manual or vacuum deaeration, pouring into standard molds, and light compaction. Curing was carried out in two stages: initially at room temperature to allow the matrix to gel, and then in an oven at 60 °C until stable mass was achieved. The specimens were then conditioned in a climatic chamber at 23 ± 2 °C and 50 ± 5% relative humidity for 48 hours before testing.

4. MATERIAL CHARACTERIZATION

The tests were divided into four groups: physical, thermal, acoustic, and biodegradability.

Physical tests included density (ASTM D792), water absorption and porosity (ASTM C272), as well as an evaluation of dimensional stability and basic mechanical strength under compression and flexure.

Thermal tests followed NCh 853, using the guarded hot plate method to determine thermal conductivity. An infrared camera measured the temperature difference across the material, allowing us to evaluate its insulating performance.

Acoustic tests were carried out using an impedance tube following ISO 10534-2, providing absorption coefficients across a frequency range of 125 to 4000 Hz. The results were compared with 30 mm expanded polystyrene (EPS) as a reference.

Data analysis included a factorial ANOVA to identify significant interactions among variables, followed by Tukey's post hoc tests.

We conducted a biodegradability test following ASTM D6400-04 by preparing and burying test specimens under controlled conditions for six weeks and recording their progressive degradation to predict their composting behavior.

5. VALIDATION IN AN APPLIED CONTEXT

As a final step, we performed an application simulation at the La Cisterna Intermodal Station by modeling the platform in CAD software and applying the experimentally determined properties to its surfaces. Using acoustic and thermal simulation tools (Odeon/EASE and COMSOL Multiphysics), we evaluated the station's acoustic and thermal performance before and after panel installation.

We set a minimum performance criterion of a 3 dB(A) reduction in critical areas and improved thermal comfort. To validate these results, we built a prototype and conducted field tests in a representative area, measuring sound pressure under real-world conditions.

These procedures allowed us to evaluate the material under controlled conditions and in an urban setting, providing evidence to support its potential for implementation at scale.

RESULTS

Characterization of the developed material yielded quantitative data on its thermal, acoustic, and physical properties, along with its biodegradability potential. The main findings are presented below alongside those of the reference material (30 mm expanded polystyrene, EPS).

MATERIAL SPECIFICATIONS

TABLE 1. Physical, Mechanical, and Environmental Properties of the Optimal Formulation (70% Shell and Pectin).

PROPERTY	VALUE OBTAINED	TEST METHOD
Bulk density	0.35 g/cm^3	ASTM D792
Thermal Conductivity	0.092 W/m·K	NCh 853
Sound Absorption Coefficient (NRC)	0.62	ISO 10534-2
Water Absorption (24 h)	6.8 %	ASTM C272
Compressive Strength	0.85 MPa	ASTM D695
Biodegradability	>85% in 120 days	Composting Trial



FIGURE 1. *Test specimens prepared for thermal conductivity and acoustic absorption testing. Source: Lara Yáñez, 2024.*



FIGURE 2. *Modular panel prototype installed in a test section at La Cisterna Intermodal Station. Source: Lara Yáñez, 2024.*

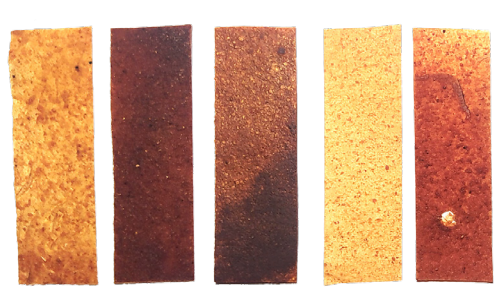


FIGURE 3. *Sound absorption coefficient measurement using an impedance tube. Source: Lara Yáñez, 2024.*

IMAGES AND PROTOTYPES

Figures 1, 2, and 3 illustrate the material characteristics of the developed panels. Material characterization helped define dimensions based on existing acoustic modules, resulting in a square format of 25 × 25 cm with a minimum thickness of 3 cm to balance acoustic and thermal performance. Different geometries were explored to ensure formal coherence in both individual units and their modular configurations. From the outset, the design incorporated manufacturing considerations, recognizing the interdependence between product and process. We analyzed angles and folds that would facilitate demolding, validating their feasibility with a wooden test mold. This stage allowed us to optimize proportions, ensure production precision, and enhance the material's performance.

BIODEGRADABILITY

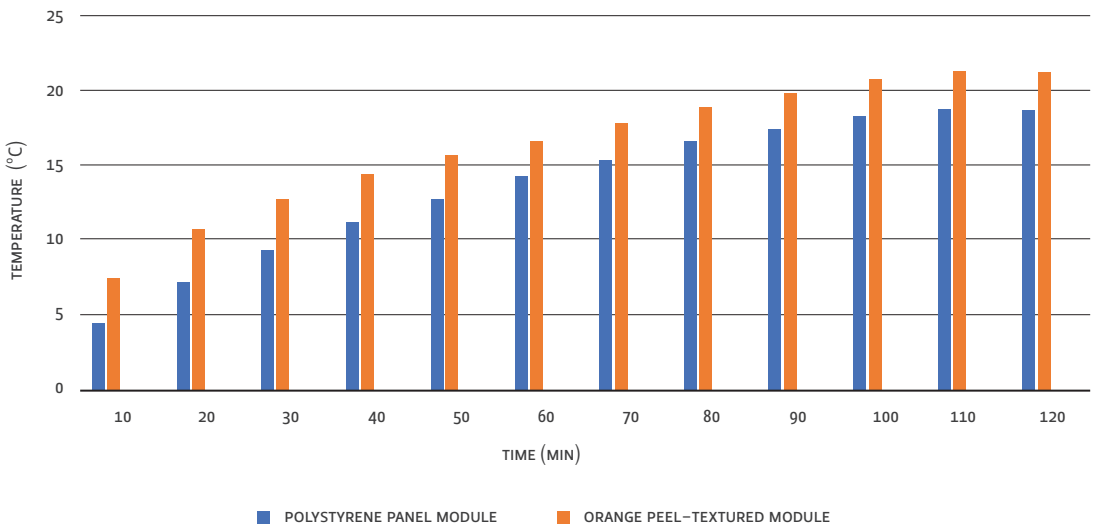
Figure 4 illustrates that the material's high hygroscopicity enabled us to predict its behavior under composting conditions—a factor that proved decisive in light of the water absorption and swelling test results. Given the decomposition rate observed in this initial test block, the material is projected to degrade within six months under extreme conditions.

THERMAL CONDUCTIVITY

Thermal conductivity results, presented in Table 2, show that the optimal orange peel bioplastic formulations achieved values between 0.08 and 0.10 W/m·K. Given the 30 mm thickness of the test plates, this performance is comparable to or better than that of the reference EPS (0.036–0.040 W/m·K).

TABLE 2. *Comparison of thermal conductivity (W/m·K).*

MATERIAL	THICKNESS (MM)	THERMAL CONDUCTIVITY (W/M·K)
EPS (reference)	30	0,038
Orange Bioplastic (70% + Starch)	30	0,085
Orange Bioplastic (70% + Pectin)	30	0,092
Orange Bioplastic (60% + Agar)	30	0,098
Orange Bioplastic (70% + Glycerin)	30	0,089



GRAPHIC 1. Biodegradation test progression over six weeks. Source: Lara Yáñez, 2024.

Graphic 1 shows temperature measurements taken every 5 minutes over a 2-hour test, comparing the proposed panels with a standard expanded polystyrene (EPS) panel. The results demonstrate that the orange peel panels have superior thermal insulation capacity, achieving a temperature differential of 21.12˚C, compared to 18.6˚C for EPS—an improvement of nearly 14% at the 120-minute mark. This improvement is attributed to the material's high porosity and spongy structure, which enhance heat retention and reduce thermal conductivity. Incorporating this material into composite insulation systems offers an efficient and sustainable alternative for thermal applications.

These results should be considered in light of the test conditions: the observed behavior corresponds to a specific scenario inside a thermal chamber, with the material positioned vertically for 120 minutes. In real-world applications, thermal performance is subject to additional external variables, such as ambient humidity and the complexity of integrating the material into building systems.

The geometry of the test panels also influenced the results. The observed 21.12 ˚C temperature differential is directly linked to the 30 mm thickness of the orange peel panel used in the test and therefore should not be taken as a universal thermal constant for the material.

SOUND ABSORPTION COEFFICIENT

Impedance tube tests showed that the optimal orange peel bioplastic formulation (70% peel and 30% binder) had high sound absorption coefficients in the mid-frequency range (400–1600 Hz), outperforming EPS in those bands, as shown in Table 3.

TABLE 3. Sound Absorption Coefficient by Frequency.

FREQUENCY (HZ)	EPS (30 MM)	ORANGE BIOPLASTIC (70%+ STARCH)	ORANGE BIOPLASTIC (70%+ PECTIN)
125	0,10	0,15	0,18
250	0,18	0,28	0,30
500	0,25	0,45	0,50
1000	0,30	0,65	0,70
2000	0,32	0,68	0,72
4000	0,35	0,70	0,75

Figure 2 compares the frequency-dependent sound absorption curves of the EPS and orange peel panels.

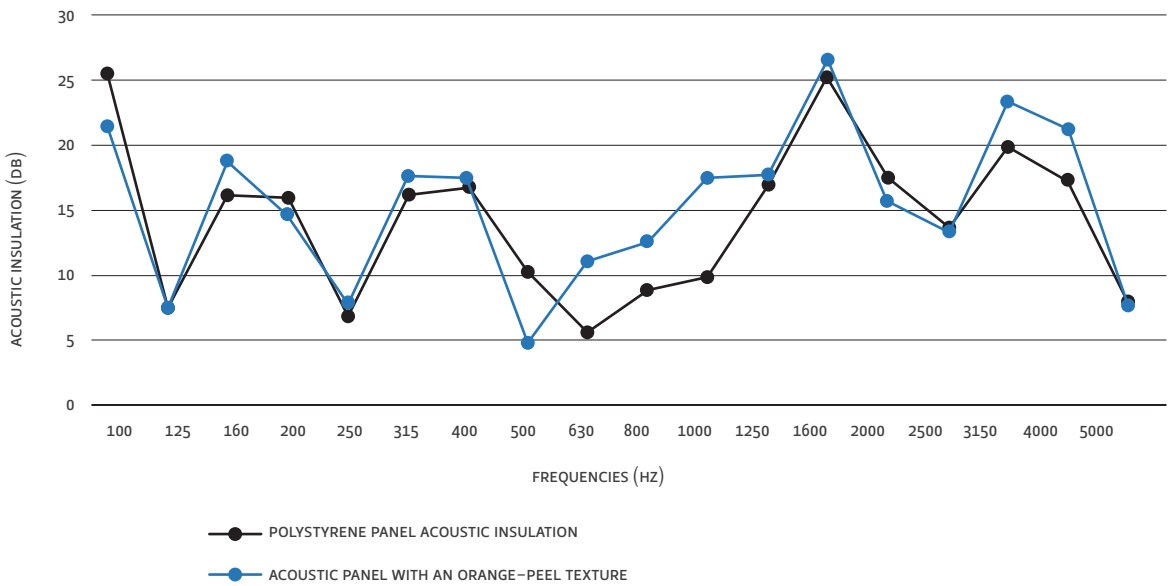


FIGURE 2. Sound absorption curves by frequency. Source: Lara Yáñez, 2024.

Figure 2 shows that the orange peel panel has lower sound insulation performance at low frequencies (100–400 Hz) than expanded polystyrene. However, between 630 and 1600 Hz, the panel consistently outperforms EPS, with peak performance at 1000 Hz, where it achieves 82% greater sound insulation. At low frequencies, EPS performs better; at higher frequencies, the proposed panel's superior performance is due to the porosity of the orange peel, whose intercellular structure absorbs shorter-wavelength sound waves. When analyzed by frequency range, the orange peel prototype performs best in the midrange (500–1600 Hz), with the exception of 500 Hz. The maximum recorded sound insulation was 25.83 dB at 1600 Hz. While EPS performs better initially, the proposed panel improves as frequency increases. Overall, the orange peel panel outperforms EPS at 12 of the 18 frequencies analyzed, confirming its effectiveness in the mid-to-high range and demonstrating its potential as an alternative acoustic insulation material.

DISCUSSION

These findings position the developed material alongside conventional insulation products such as expanded polystyrene (EPS). Thermal characterization yielded conductivity values of 0.08–0.10 W/m·K—higher than EPS (≈0.038 W/m·K)—yet sufficient for low- to medium-demand applications, particularly in temperate climates like the Santiago Metropolitan Region. Biomaterials literature indicates that lignocellulosic composites generally have higher thermal conductivity than petroleum-based polymers due to their porous, heterogeneous structure (González Donoso, 2020; Rupal and Tank, 2025). However, this disadvantage is offset by low density, renewability, and biodegradability—key circular economy attributes. The findings further highlight that the material's high hygroscopicity enabled us to predict its composting behavior, confirming the relevance of the absorption and swelling tests. Complete biodegradation in approximately six months under extreme conditions reinforces its potential as a sustainable alternative for construction.

Acoustically, the absorption coefficients measured at mid and high frequencies (400–2000 Hz) significantly exceeded those of EPS, with an NRC of 0.62 compared to 0.32 for the reference material. These results align with previous studies on plant-fiber biocomposites (Tedjosaputro et al., 2024), showing that internal heterogeneity and microporosity enhance sound energy dissipation. This finding is particularly relevant to the La Cisterna Intermodal Station, where dominant noise—from bus engines and heavy foot traffic—falls within these frequency bands. In public health terms, this suggests a potential to reduce users' noise-induced stress, consistent with WHO (2022) guidelines on urban noise exposure.

The advantages over conventional insulation materials fall into three categories: environmental, social, and technical. Environmentally, using orange peels as a raw material offers a way to valorize agro-industrial waste that would otherwise become highly polluting organic waste. Moreover, the material is biodegradable and compostable, helping to complete the material life cycle and reducing construction-related carbon footprints. Socially, developing waste-based materials creates opportunities

for local value chains and collaborations among the agricultural sector, the construction industry, and academia—fostering regional innovation. Technically, the modularity of the panels facilitates their integration into existing building systems and allows for customization across applications such as partition walls, acoustic ceilings, and cladding.

Scaling up this material faces significant challenges. A key limitation is the variability of the raw material, as the chemical composition of orange peels can vary with season, fruit variety, and processing conditions. This can affect the consistency of the material's properties, making it necessary to establish classification standards and pretreatment protocols. Another constraint is its limited mechanical strength relative to synthetic materials, which restricts structural applications and positions it primarily as a complementary insulator or coating. Industrial-scale production also faces cost barriers: although the raw material is abundant and low-value, the drying, grinding, and curing processes are energy- and time-intensive, potentially raising production costs compared to mass-produced conventional insulation.

Building codes are central to industry acceptance. In Chile, material certification primarily hinges on compliance with NCh standards, requiring bioplastics to be validated in accredited laboratories and undergo full-scale testing before adoption in public or private projects. However, the global push for sustainable construction and the SDGs creates opportunities for incorporating innovative materials into infrastructure tenders, particularly for projects pursuing certifications such as LEED, BREEAM, or CES.

Finally, the discussion of this material's viability should extend beyond technical performance to include its systemic impact. As the Ellen MacArthur Foundation (2015) argues, the true potential of biomaterials lies not simply in replacing synthetic polymers, but in transforming the relationship between waste and resources to create regenerative production cycles. Ultimately, the modular orange peel bioplastic panel is not merely an alternative to conventional insulation—it exemplifies a model of sustainable innovation that integrates design, science, and environmental awareness.

CONCLUSION

This research demonstrates the feasibility of developing a modular insulation panel from orange peel bioplastics and plant-based binders as an alternative to conventional expanded polystyrene (EPS). EPS is the most widely used thermal and acoustic insulator in construction, owing to its low cost, light weight, ease of installation, and broad availability. Its market dominance positions it as the minimum performance benchmark against which new sustainable alternatives must be measured. Although materials like glass wool offer good properties, they are more expensive and difficult to install, reinforcing the preference for EPS. In this context, comparing the orange peel biocomposite with EPS is methodologically essential: the material's 14% superior thermal performance and competitive acoustic properties confirm its potential as a technically viable and sustainable construction alternative.

The optimal formulations exhibited thermal conductivity values of 0.08–0.10 W/m·K, a sound absorption coefficient (NRC) of approximately 0.62 (for the 70% peel and pectin composition), and over 85% biodegradability in accelerated composting tests. Although this thermal performance does not match that of high-performance polymeric insulators such as EPS, the bioplastic offers a compelling balance of acoustic absorption, low density, and environmental benefits—including waste recovery and compostability. This positions it as a strong candidate for non-structural applications where acoustic and thermal comfort are priorities, such as cladding, modular platform panels, acoustic ceilings, and partitions.

These results align with trends reported in the literature on lignocellulosic materials and biocomposites, particularly regarding their acoustic behavior. The porous, heterogeneous microstructure of these composites enhances sound energy dissipation, yielding high absorption coefficients in the mid- to high-frequency ranges, consistent with previous studies. However, the presence of biogenic components and trapped air within the matrix contributes to higher thermal conductivity than closed-cell synthetic foams, posing energy efficiency challenges. To address this, the literature proposes design strategies—such as modulated geometries, air chambers, and multilayer systems—to compensate for lower thermal resistance without compromising acoustic performance. The orange peel bioplastic aligns well with current research: it offers strong sound absorption, environmental benefits, and adaptability to modular manufacturing. Its adoption could also enable local value chains, reduce logistics costs, and generate employment, provided that collection and processing systems are properly coordinated. These functional, environmental, and socioeconomic advantages reinforce its viability as a sustainable alternative to conventional insulation, although technical challenges persist and must be addressed through integrated design and construction strategies.

SCALABILITY POTENTIAL AND IMPLEMENTATION CHALLENGES IN THE INDUSTRY

The scalability of this biocomposite presents a concrete opportunity to integrate material innovation, regional sustainability, and productive development. A key strategy is to establish direct links with citrus processing plants or juice companies, ensuring a constant, consistent, and traceable supply of citrus peel. Pilot plants and batch production would help optimize critical processes such as drying and grinding, promoting energy savings via heat recovery and efficient resource use. In its initial phase, the material is best suited for contexts with low structural demands but high environmental requirements—such as platform surfacing, acoustic panels in stations, or interior partitions in public buildings. These applications could benefit from environmental certifications (LEED, BREEAM, CES), positioning it as a competitive alternative to conventional insulation.

Integrating it into the industry involves technical and regulatory challenges that require strategic attention. Seasonal variability in the raw material—affecting variety, moisture content, and pectin and cellulose composition—calls for robust sorting and pretreatment protocols, including particle size control and rapid quality testing. Mechanical properties and resistance to moisture, UV radiation, and biological agents will require design improvements, such as encapsulation or integration with rigid substrates. Additionally, aging and fire resistance tests are essential to meet regulatory requirements.

The lack of specific bioplastic standards in civil engineering and public transport calls for collaboration with accredited laboratories to validate compliance with NCh standards and building codes. Furthermore, the energy costs of processing—particularly

drying and grinding—must be optimized through heat recovery, renewable energy use, and circular economy principles. Finally, safety aspects related to flammability and volatile organic compound (VOC) emissions require rigorous evaluation, incorporating physical barriers or flame retardants that align with sustainability criteria.

RECOMMENDATIONS FOR COATINGS OR ENCAPSULATION TO ENHANCE PERFORMANCE IN REAL-WORLD CONDITIONS

To extend the application of orange peel panels beyond the laboratory and ensure reliable performance under moisture, friction, and intensive use, coating or encapsulation strategies are essential. These must protect the material without compromising its bio-based character or circular economy potential. Given that tests revealed high water absorption and significant swelling—attributed to the hygroscopic nature of the peel's pectin, cellulose, and hemicellulose—limiting direct moisture exposure is critical. We recommend natural or mineral-based coatings, such as vegetable waxes, mineral emulsions, or biodegradable seals based on modified polysaccharides. These form a surface film that slows water ingress while maintaining breathability, thus preventing internal condensation and preserving structural integrity.

In applications where the panel is exposed to foot traffic, friction, or vandalism—as at La Cisterna Intermodal Station—it is advisable to avoid leaving the biocomposite directly exposed. Instead, it should be integrated into a sandwich-type encapsulation system, where the panel serves as the insulating core protected by a more durable outer layer that absorbs impact and wear. These outer layers may consist of thin wood laminates, low-density fiberboard, micro-perforated panels, or acoustic panels that preserve the core's thermal and acoustic properties while shielding it from physical damage. This strategy not only offers protection but also facilitates maintenance and extends the system's service life.

When preserving visible sound absorption is essential, covering the panel with technical fabrics, breathable mesh, or nonwoven geotextiles offers a practical alternative. This type of finish provides a protective barrier against dust, dirt, and abrasion while enabling sound to reach the absorptive core without compromising its acoustic properties. It also offers the added advantage of replaceability, supporting a maintenance-oriented design strategy and contributing to lifecycle extension.

Finally, any proposed solution should incorporate disassembly and material separation criteria, allowing the panel to be removed, maintained, or recycled without relying on permanent joints. Avoiding rigid, thermoset, or permanently bonded coatings is essential to preserving the compostability or future reuse of the orange peel core.

Partnering with small and medium-sized enterprises offers a strategic route to scaling this solution, particularly through public policy projects that coordinate training, local implementation, and access to government funding for sustainability, innovation, and entrepreneurship.

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