BIO-AGGLOMERATED PANELS MADE FROM FOREST WASTE: THE CASE OF EUCALYPTUS GLOBULUS LABILL

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RECEIVED: OCTOBER 15, 2025 // **ACCEPTED:** JANUARY 19 2026

THIS RESEARCH DESCRIBES THE PROCESS OF DESIGNING, DEVELOPING, AND VALIDATING BIO-AGGLOMERATED PANELS MADE FROM CAPSULES OF EUCALYPTUS GLOBULUS LABILL, AN INVASIVE SPECIES WITH A HIGH ENVIRONMENTAL IMPACT IN CHILE. CONDUCTED AS A YEAR-LONG THESIS PROJECT, THIS APPLIED RESEARCH FOCUSES ON THE DEVELOPMENT AND TECHNICAL VALIDATION OF A BIOMATERIAL THROUGH A COLLABORATIVE RESEARCH-THROUGH-DESIGN PROCESS INVOLVING STUDENTS AND TEACHERS. ITS PURPOSE WAS TO EXPLORE THE TECHNICAL AND SUSTAINABLE FEASIBILITY OF TRANSFORMING FOREST WASTE INTO A FUNCTIONAL MATERIAL, USING DESIGN METHODOLOGIES FOCUSED ON MATERIAL EXPERIMENTATION AND THE CIRCULAR ECONOMY. THE RESEARCH WAS STRUCTURED ACCORDING TO THE MATERIAL DRIVEN DESIGN (MDD) AND TERRITORY-BASED BIOMATERIALS (BBT) APPROACHES, INTEGRATING STAGES OF TERRITORIAL DIAGNOSIS, CHARACTERIZATION OF RAW MATERIALS, FORMULATION AND MANUFACTURE OF MIXTURES, APPLICATION OF PHYSICAL-MECHANICAL TESTS, AND ANALYSIS OF RESULTS. THE PANELS ACHIEVED AN AVERAGE DENSITY OF 0.82 G/CM^3, WATER ABSORPTION OF 6.3%, AND TENSILE STRENGTH OF 11.4 MPA, DEMONSTRATING STRUCTURAL STABILITY AND LOW PERMEABILITY. THE TECHNICAL AND MATERIAL RESULTS OBTAINED PLACE BIO-AGGLOMERATED PANELS WITHIN THE RANGE OF LOW-DENSITY LIGNOCELLULOSIC MATERIALS WITH POTENTIAL APPLICATIONS IN INTERIOR DESIGN. BEYOND THE TECHNICAL RESULTS, THE WORK RECOGNIZES THE EDUCATIONAL CONTEXT IN WHICH THE RESEARCH WAS CONDUCTED, WITHOUT THIS DIMENSION CONSTITUTING AN OBJECT OF STUDY IN ITSELF, DEMONSTRATING THAT UNDERGRADUATE ACADEMIC PRACTICE CAN CONTRIBUTE TO THE GENERATION OF APPLIED KNOWLEDGE IN SUSTAINABLE DESIGN.

KEYWORDS: EUCALYPTUS GLOBULUS LABILL, BIOMATERIALS, SUSTAINABLE DESIGN, CIRCULAR ECONOMY, INVASIVE SPECIES

1. REDEFINING WASTE: E. GLOBULUS AS A DESIGN RESOURCE

A core challenge for contemporary design is to address the environmental damage caused by linear production models. These models are characterized by intensive resource extraction, energy-heavy manufacturing, and waste that cannot re-enter natural cycles. This linear system, sustained for decades by the global economy, has contributed significantly to biodiversity loss, soil degradation, and an increase in the global carbon footprint. In this context, design has broadened its scope, moving from a practice focused on the production of objects, spaces, and services to a discipline capable of generating applied knowledge, particularly in areas related to sustainability, materiality, and territory.

Biomaterials are emerging as a relevant response to these challenges, offering alternatives that combine material innovation, the use of local resources, and reduced environmental impact. The potential of agricultural and forestry waste as a raw material for biocomposites has been highlighted in several studies. This approach reduces dependence on conventional materials and promotes circular economy models (Parisi & Rognoli, 2020; Ellen MacArthur Foundation, 2021).

Among Chile's most critical environmental problems is the uncontrolled spread of E. globulus, an exotic species introduced on a massive scale by the forestry industry due to its rapid growth and economic profitability. However, its widespread use has caused a significant ecological imbalance: it competes with native species for water and nutrients, impoverishes soils due to its acidic pH, and its high flammability increases the risk of forest fires (Chilean Forestry Institute [INFOR], 2022; Ministry of the Environment [MMA], 2023). At the same time, capsules (the woody fruit of the eucalyptus tree), whose biological function is to contain, protect, and release seeds once they reach maturity, generally in response to favorable environmental conditions, are produced in annual volumes estimated at more than one million tons in the Biobío Region alone. Currently discarded and unused, these capsules represent a highly available forest waste product with low economic value and no systematic recovery strategies.

In light of this scenario, the present study investigates the underexplored technical potential of E. globulus capsules for developing biomaterials applicable in design. The guiding research question is: Can bio-agglomerated panels made from E. globulus capsules be developed with physical and mechanical properties suitable for interior design and furniture applications?

This research was conducted as a year-long university thesis under the supervision of a two-person team specialized in design research, alongside other faculty experts in materials science, sustainability, and environmental chemistry. This approach allowed for the simultaneous integration of interdisciplinarity between the scientific rigor of applied research and the educational orientation characteristic of the educational process. Through weekly meetings, laboratory sessions, and progress reviews, the student-teacher relationship was consolidated as a fundamental methodological axis, articulating critical reflection on design with experimental practice using materials. This collaborative structure allowed the research to advance in parallel along two complementary dimensions: on the one hand, the technical and material dimension, focused on validating the properties of bio-agglomerated panels; and on the other, the pedagogical dimension, focused on learning, project decision-making, and knowledge generation through the practice of design.

The overall objective of the study was to evaluate the feasibility of producing bio-agglomerated panels from E. globulus capsules using design methodologies focused on material experimentation and sustainability. To achieve this goal, the following specific objectives were defined:

1. Analyze the physical and chemical properties of plant waste to determine its viability as a raw material.
2. Develop experimental bio-agglomerate formulations using natural biopolymers.
3. Manufacturing panels using controlled thermal pressing processes.
4. Evaluate the physical and mechanical properties (density, water absorption, tensile strength, and abrasion) of the material obtained in accordance with recognized technical standards (UNE-EN 323, UNE-EN 317, ASTM D1037, and EN 14323).
5. Analyze the performance of bio-agglomerated panels in relation to comparable lignocellulosic materials reported in the literature.

2. METHODOLOGY

The research was conducted using an applied research approach, combining design logic with procedures typical of experimentation in materials science. The methodology was structured around the integration of the MDD and BBT approaches, adapted to an academic context of guided research.

It should be noted that the development of this research is currently in the process of being patented, which is why certain technical aspects associated with the experimental procedures, specific formulations, and manufacturing parameters cannot be described in detail at this time. Consequently, the methodology outlined prioritizes the description of the conceptual approach, the methodological frameworks adopted, and the general criteria for design and experimentation, safeguarding the confidentiality necessary for the protection of intellectual property without compromising the scientific validity or conceptual reproducibility of the study.

Firstly, the MDD methodology (Karana et al., 2015) places the material at the center of the design process, promoting understanding of its sensory, technical, and cultural properties. This approach suggests that material knowledge is constructed iteratively, based on empirical exploration and dialogue between the design vision and scientific evidence. Secondly, the BBT methodology (Weiss Münchmeyer & Besoain Narvaez, 2022) was adopted, which proposes the development of materials based on local resources, valuing the ecological, cultural, and productive identity of the territory. The combination of both approaches allowed us to adapt our own interdisciplinary methodology to the case study, integrating design criteria, sustainability, and material properties.

On the other hand, the link between design and sustainability is also articulated with the principles of the circular economy (Calderón et al., 2024), which seeks to replace the linear model of extract-manufacture-dispose with a regenerative model based on the continuous cycle of resources. According to the Ellen MacArthur Foundation (2021), 80% of a product's environmental impact is determined at the design stage, making designers key players in the transition to sustainable production models. In this sense, the development of biomaterials from local waste not only represents a technical innovation but also an epistemological transformation of the role of the designer, who goes from being a formal mediator to becoming an agent of environmental and social change (Pieroni et al., 2019).

The use of E. globulus capsules is based on their status as forest waste associated with a rapidly spreading exotic species, which allows us to address an ecological problem linked to the accumulation of biomass without valorization. At the same time, its use as an alternative raw material responds to industrial demand for sustainable materials, as it is a renewable, locally available, and underutilized resource. This strategy helps reduce pressure on virgin natural resources, boosts local economies by generating added value for the region, and expands sources of material innovation, aligning with circular economy and sustainable design approaches. At the national level, this line of research is aligned with Chile's National Circular Economy Strategy (MMA, 2023) and the United Nations 2030 Agenda (2015), whose sustainable development goals 9, 12, and 15 promote sustainable production, responsible innovation, and the conservation of terrestrial ecosystems.

Furthermore, the research responds to an emerging need in design education: to develop scientific and technical skills that enable sustainability challenges to be addressed from an interdisciplinary perspective (Kolb, 1984). The training process involved acquiring skills in the experimental field, data analysis, methodological documentation, and scientific communication, which are essential aspects for the professionalization of contemporary design as an agent of change. In this context, teacher mentoring played a central role in guiding decision-making, ensuring methodological consistency, and stimulating critical reflection. Thus, the work transcends its technical value and positions itself as a comprehensive educational experience, in which practical learning is linked to the production of knowledge applicable to the territory.

2.1 METHODOLOGICAL ADAPTATION

The development of this research was methodologically structured around the convergence between material experimentation and design reflection (Figure 1). From its inception, the project was framed within an applied research strategy based on empirical observation, iteration, and systematic evaluation of results. The methodology adopted combines the principles of MDD and BBT. This integration made it possible to link design logic with the procedures of materials science, creating a hybrid process that combines technical knowledge, ecological awareness, and collaborative learning.

2.1.1 METHODOLOGICAL APPROACH AND GENERAL STRUCTURE

The methodological approach of the project was based on a sequence of four main stages:

- Territorial diagnosis and characterization of waste.
- Preparation of raw materials and experimental formulation.
- Manufacture and pressing of panels.
- Physical-mechanical evaluation and comparative analysis of results.

Each of these stages was accompanied by review sessions and academic mentoring, during which technical decisions, protocol adjustments, and the interpretation of partial results were discussed.

2.2 TERRITORIAL DIAGNOSIS AND CHARACTERIZATION OF WASTE

The work began with a territorial exploration phase focused on identifying and evaluating plant waste. The Metropolitan Region was selected, where E. globulus has a high distribution density and constitutes a potential source of untapped biomass. The collection was carried out in urban areas near the Las Condes district during the months of June to October, considering only ripe and dry capsules that had fallen naturally from the tree, in order to avoid additional environmental impact.

The capsules (Figure 2) were studied according to the literature to determine their basic chemical composition and physical characteristics. The results found show a high content of lignin (28%) and cellulose (45%), with the presence of natural compounds such as eucalyptol, known for its hydrophobic and antibacterial properties (Amaya, 2020). This chemical profile justified its selection as a raw material for bio-agglomerated panels with low absorption and good structural resistance, as well as antifungal properties.

2.3 PREPARATION OF RAW MATERIALS

The collected Eucalyptus globulus capsules underwent a standardized pretreatment process aimed at removing impurities, stabilizing moisture content, and obtaining a controlled particle size distribution in order to ensure material homogeneity and experimental process reproducibility.

The material was first washed with water to remove surface residues. Its initial moisture content was then determined using a moisture chamber to define the appropriate drying conditions. Drying was performed in a convection oven until a moisture level suitable for grinding was achieved, thus preventing thermal alteration of the lignocellulosic material (Figure 3).

Once dry, the material was reduced in size using mechanical grinding systems, including a disc mill, to obtain a controlled particle size. The ground material was then sieved, selecting particles with diameters between 0.2 and 0.4 mm, a range considered suitable for promoting homogeneous distribution of the plant reinforcement and correct interaction with the matrix during the formulation stage (Figure 4).

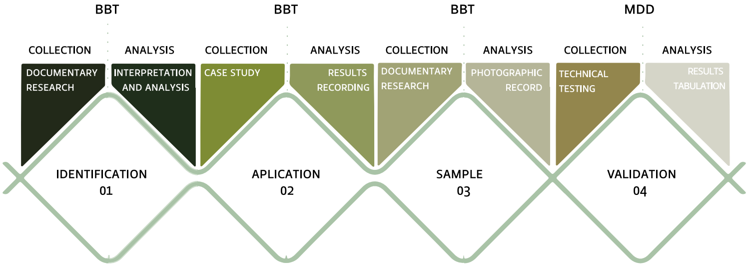

FIGURE 1. Methodology design, based on the double diamond methodology, Design Council. It represents the sequence of stages from waste collection to experimental validation, integrating instances of observation, analysis, and guided reflection.

FIGURE 2. Capsules collected from E. globulus. Note their spherical shape and rough texture, which are key factors in the grinding and homogenization processes.

TABLE 1. PRE-TREATMENT STAGES FOR E. GLOBULUS CAPSULES

NATURAL ASSOCIATION	DESCRIPTION	QUALITIES
Washing	Paddle mixer for several minutes	Removal of surface impurities
Drying	Convection oven at 50–70 °C	Moisture reduction to 5%
Grinding	Disc mill at 1400 rpm	Particles measuring 0.2–0.4 mm

FIGURE 3. Drying process. Drying was conducted by evenly distributing the capsules in an oven to drive off internal moisture.

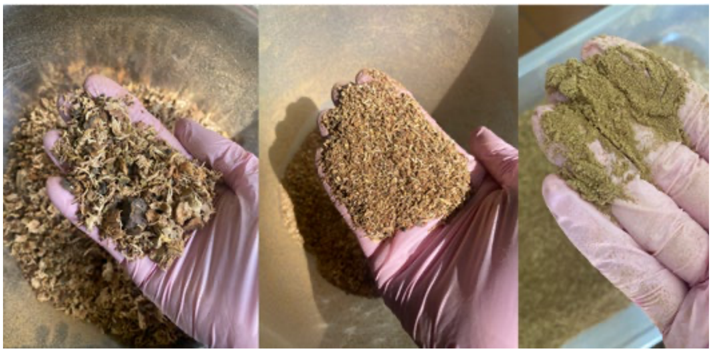

FIGURE 4. Grinding process. Uniform reduction of capsule particle size.

2.4 FORMULATION AND TESTING OF MIXTURES

The formulation stage consisted of developing three experimental compositions (A, B, and C) of bio-agglomerated panels, using the sawdust obtained as a base and combining it with different natural biopolymers: agar-agar, sodium alginate, and natural resins. The proportions of the components were defined through preliminary cohesion and density tests, following iterative procedures inspired by the MDD model.

It should be noted that the specific components used in each formulation, as well as their exact proportions and the detailed conceptual or technical differences between formulations A, B, and C, cannot be disclosed in this document because it is in the process of being patented. However, in general terms, it can be said that in formulation A, the main component is a naturally occurring resin; in formulation B, it is a synthetic resin; and in formulation C, it is a naturally occurring plasticizer, also known as a hydrocolloid.

Each mixture was subjected to controlled heating until it reached a uniform viscosity before being poured into metal molds. The pressing test conditions were set at 50-70 °C for 90 minutes, at constant pressure, according to recommendations in the technical literature on lignocellulosic biocomposites (Pieroni et al., 2019) (Figure 5).

2.4.1 MANUFACTURING AND PRESSING

Once the formulations had been defined, the mixtures were poured into 200 × 200 × 10 mm steel molds (Figure 6). The panels were pressed in a thermal hydraulic press and then pressed with brackets to be subjected to constant heat in a convection oven. They were then left to rest for 24 hours at room temperature to stabilize before testing.

A relevant aspect was the supervision and verification of pressure and time parameters, ensuring the reproducibility and safety of the procedure. The practical experience of the teachers facilitated the interpretation of the chemical reactions observed, such as agar gelatinization and lignocellulosic adhesion, which were decisive for the final performance of the material. This was documented through photographic records and control sheets, which strengthened scientific learning and the traceability of the process.

2.5 PHYSICAL–MECHANICAL EVALUATION AND EXPERIMENTAL VALIDATION

The samples obtained were subjected to standardized tests in accordance with UNE-EN 323, UNE-EN 317, ASTM D1037, and UNE-EN 12323 standards for lignocellulosic materials, evaluating bulk density, water absorption, tensile strength, and surface abrasion (Figure 7).

Comparative analysis of the three formulations showed that variant A offered the best balance between density and strength, and was selected as the basis for the validation phase (Figure 8).

FIGURE 5. Composite panel made from a mixture of biopolymers and vegetable sawdust. The image shows the homogeneous integration of the components before molding and pressing.

FIGURE 6. Experimental panels during the pressing process. The image shows the homogeneous compaction across the panel.

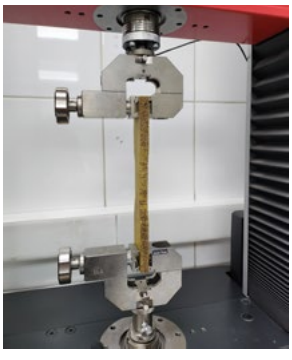

FIGURE 7. Tensile tests. The trials confirm the material's dimensional stability and resistance under tensile loading.

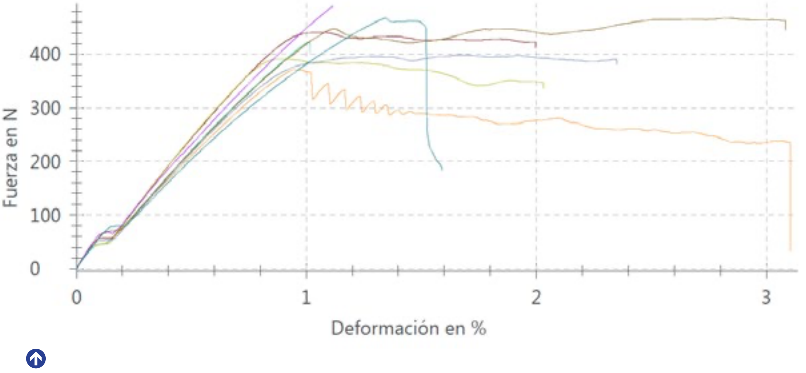

FIGURE 8. Triplicate tensile tests on formulations A, B, and C. The tests demonstrate the different strengths of the materials.

2.6 COMPARISON WITH PREVIOUS STUDIES

The results obtained from the material formulations show similarities and advances with respect to previous research on bio-agglomerates made from agricultural and forestry waste, as well as in relation to reference industrial materials such as MDF (medium-density fiberboard), used in this study as a comparative parameter to assess competitiveness in the current panel market. For example, Seguí et al. (2018) developed panels using rice husks and starch biopolymers. Similarly, Micheloud (n.d.) evaluated panels made from pine resin and cork, achieving good cohesion but lower density. On the other hand, the case of Schwarz (n.d.) was analyzed to compare how the values obtained in this research reflect a more favorable balance between lightness and strength, which supports the relevance of the selected formulation (Figure 9).

PROJECT	PROJECT AND AUTHOR	RECIPE DIFFICULTY	RESULT
	Sawdust – Agar Agar – ra01 Tamara Schwarz	1/5	• 50 grams (g) of Eucalyptus globulus sawdust • 15 grams (g) of agar agar • 5 grams (g) of glycerol • 250 milliliters (ml) of water
	Sawdust – Damar Resin Saw04 Tamara Schwarz	1/5	• 4.5 grams (g) of damar resin • 3 grams (g) of Eucalyptus globulus sawdust
	Sawdust – Agar – Starch Saw02 Tamara Schwarz	1/5	• 15 grams (g) of agar agar • 5 milliliters (ml) of glycerol • 250 milliliters (ml) of water • 5 milliliters (ml) of cornstarch • 50 grams (g) of Eucalyptus globulus sawdust
	Sawdust – Dextrin Saw05 Tamara Schwarz	3/5	• 3.5 grams (g) of dextrin • 3.5 grams (g) of water • 3 grams (g) of Eucalyptus globulus sawdust

FIGURE 9. State-of-the-art E. globulus recipes. Own elaboration (2023), presenting different case studies that use the raw material for biomaterial development.

3. RESULTS

The results of this research are structured based on the experimental findings obtained during the material evaluation phase, which allow for a comprehensive analysis of the performance of the bio-agglomerate developed from E. Globulus capsules. These results demonstrate the technical viability of the material and provide relevant information about its physical, mechanical, and sensory properties, contributing both to the analysis of its potential in terms of material sustainability and to the strengthening of applied knowledge in the field of design and biomaterials.

3.1 PHYSICAL-MECHANICAL EVALUATION

The tests quantified the performance of the material under controlled conditions. The most relevant results are summarized below:

TABLE 2. RESULTS OF PHYSICAL-MECHANICAL TESTS

FORMULATION	DENSITY [1]	WATER ABSORPTION[2]	TENSILE TEST[3]	ABRASION[4]
A	0,82	6,3 %	11,4	4,2
B	0,76	10,8 %	7,9	6,8
C	0,71	15,0 %	5,6	8,1
MDF	0,72	30-60 %	0,65	Does not comply

The table presents the physical-mechanical tests performed on formulations A, B, and C, indicating for each one the type of test, its unit of measurement, and the technical standard of reference used. Density1 (g/cm^3) was determined in accordance with ASTM D1037 to evaluate the compaction and homogeneity of the material. Water absorption2 (%) was measured according to EN 317, allowing the hygroscopic behavior of the material when exposed to moisture to be characterized. The tensile test3 (MPa), performed in accordance with ASTM D638, analyzed the material's mechanical strength under tensile stress. Finally, abrasion4 resistance (mm/min), evaluated in accordance with UNE 56-537, was used to estimate the surface wear of the material under controlled friction.

The results corroborate the technical suitability of the material, especially in terms of density and strength. The density achieved by formulation A is in the range of low-density agglomerates (0.6-0.8 g/cm^3), while its tensile strength exceeds the average values recorded in similar materials made from lignocellulosic waste (Pieroni et al., 2019).

3.2 SENSORY AND AESTHETIC CHARACTERIZATION

Beyond its technical properties, the material has sensory qualities that are relevant from a design perspective. The panels obtained have a uniform texture, a matte surface, and a natural brown color with warm tones, derived from the oils in the eucalyptus. In relation to the olfactory dimension, a noticeable aroma is present in certain formulations, with characteristic notes of eucalyptus; this aroma remains after the thermal pressing process, persisting in a mild and non-invasive way in the final material (Figure 10). The absence of synthetic resins also gives it an organic feel, all factors valued in interior design and eco-friendly furniture applications.

FIGURE 10. Final bio-agglomerated panel after thermal curing. Note the uniform surface, adequate compaction, and natural color of the material without chemical additives.

4. DISCUSSION

The discussion of the results allows us to interpret the experimental findings in light of the theoretical framework, as well as to explore their potential implications for sustainable design in academic and territorial contexts. In this regard, the results obtained suggest the initial technical viability of bio-agglomerated panels made from E. Globulus capsules, while highlighting the importance of teaching support in consolidating technical and methodological learning during the experimental process. Rather than establishing conclusive effects, this section seeks to place the results within a field of possibilities, identifying the scope, limits, and projections of the material developed.

4.1 TECHNICAL AND ENVIRONMENTAL RELEVANCE

From a technical perspective, the physical-mechanical performance of the developed material falls within the ranges reported for low-density lignocellulosic biocomposites, according to information available in the specialized literature (Food and Agriculture Organization of the United Nations [FAO], 2021; Pieroni et al., 2019). The average density obtained and the tensile strength values indicate structural behavior consistent with low mechanical demand applications, particularly in areas such as interior design, lightweight furniture, or decorative elements. Similarly, the water absorption recorded suggests a favorable response to normal environmental humidity conditions, which could be related to the presence of naturally hydrophobic compounds in eucalyptus capsules (Amaya, 2020). However, these results should be understood as exploratory, given that they are obtained in a controlled context and on an experimental scale carried out in a laboratory.

In environmental terms, the use of capsules, currently considered forest waste, can be interpreted as a material recovery strategy, aligned with the principles of the circular economy, which promote the extension of the life cycle of resources and the reduction of the use of virgin raw materials (Ellen MacArthur Foundation, 2021). Rather than confirming a direct impact on environmental mitigation, the results allow us to project the potential of the material as an alternative to conventional processes, in line with national guidelines aimed at waste recovery and sustainable innovation (MMA, 2023).

In this context, E. Globulus, often approached from a problematic perspective in ecological terms, is reinterpreted in this research as a resource susceptible to material valorization. This conceptual shift does not imply ignoring the debates associated with forest management, but rather exploring new interpretations from a design perspective, where design practice acts as a mediator between waste, material, and productive context. This approach interacts with contemporary perspectives that attribute an active role to design in the articulation between productive systems and ecosystems (Badhoutiya et al., 2023).

4.2 TECHNICAL INTERPRETATION

Low water absorption reinforces the hypothesis of adequate dimensional stability for interior applications, which expands its possibilities for use in cladding, furniture, or decorative panels. These properties, together with its texture and material origin, strengthen its potential as an expressive material in the field of design, allowing it to communicate values of sustainability, local provenance, and low environmental impact. In this regard, the MDD methodology proved key to integrating perceptual and symbolic dimensions into the evaluation of the material (Karana et al., 2018).

The experimental results confirm that the combination of agar-agar and vegetable glycerol acts as a functional biopolymer, promoting the adhesion of lignocellulosic particles. The interaction between the hydroxyl groups in agar and compounds present in the capsules could explain the mechanical resistance observed and the limited moisture absorption, although these mechanisms require validation through complementary analyses. Likewise, the porous structure observed after thermal pressing contributes to its lightness and sound insulation capacity, an additional property that could be explored in future research. Overall, the results support the initial technical feasibility of developing biomaterials from local plant waste, under the criteria of low energy impact and absence of toxic components.

4.3 TEACHING SUPPORT

Teacher support played a central role in conducting the experimental process, particularly in managing the uncertainty inherent in material experimentation. Pedagogical mediation made it possible to transform errors, formulation mistakes, and unexpected results into learning opportunities, strengthening technical and methodological understanding. This dynamic aligns with project-based learning (PBL) approaches, widely recognized in design education for their ability to articulate theory, practice, and critical reflection (Almulla, M.A., 2020).

4.4 TERRITORIAL AND INTERDISCIPLINARY PROJECTION

The connection between design and territory emerges as one of the relevant projections of this research. The use of local waste for biomaterial exploration presents opportunities to strengthen links between academia, industry, and the community, especially in contexts where there is underutilized biomass available. Although it is not possible to confirm direct impacts in terms of employment or reduced pressure on native resources, the study suggests potential for integration into local value chains, particularly when the resource comes from managed forest plantations or urban contexts, an aspect that should be carefully considered in future developments.

Within the Chilean context, research into biomaterials remains nascent, particularly in its coordination with public policy and in scaling up production, especially when compared to international benchmarks. However, the existence of frameworks such as the National Strategy on Climate Change and Vegetational Resources (National Forestry Corporation, 2022) opens up space for linking experimental design projects with territorial development initiatives. In this regard, this study provides a preliminary basis for future interdisciplinary collaborations between universities, municipalities, research centers, and material innovation laboratories.

5. CONCLUSION

The development of bio-agglomerated panels from E. globulus capsules demonstrates that it is possible to transform invasive forest waste into a material with practical applications. The research showed that the waste has high potential, which, when combined with natural biopolymers, can be used to produce a bio-agglomerate with physical and mechanical properties comparable to conventional panels, but with a significantly lower ecological footprint.

From a methodological perspective, combining the MDD and BBT models proved essential for integrating scientific research with the project-based thinking inherent to design. This approach allowed us to understand the material not only in terms of its chemical composition and structural behavior, but also in terms of its aesthetic, sensory, and territorial dimensions. The adapted methodology is presented as a replicable model that can be used in other academic and territorial contexts for the creation of sustainable materials derived from local resources.

Constant guidance and critical support enable experimentation to be structured, promoting informed decision-making and the systematization of results, which are key aspects for the transferability of knowledge beyond the immediate educational context. Likewise, interdisciplinary discussion broadens interpretative frameworks, integrating technical, scientific, and design knowledge, which contributes to a deeper understanding of material processes. In this scenario, practical learning transcends exploratory exercise and becomes an instance of knowledge production, insofar as the results are documented, analyzed, and contrasted with existing theoretical frameworks. In this way, teaching acts as a mediator between creativity and experimental rigor, enabling university education to generate results with social and environmental impact, at least in terms of opening up new lines of research and potential transfer.

Likewise, the results contribute to the advancement of the circular economy in Chile by proposing an alternative for the recovery of forest waste in line with the National Circular

Economy Strategy (MMA, 2023). The project also aligns with the Sustainable Development Goals (SDGs), particularly SDG 9: Industry, Innovation, and Infrastructure; SDG 12: Responsible Consumption and Production; and SDG 15: Life on Land, by promoting design practices that integrate technological innovation, responsible use of resources, and environmental restoration. Finally, this research highlights the role of design as a strategic discipline in the transition towards sustainable production systems. By placing material at the center of the design process, design is redefined as an agent of ecological and social change, capable of linking technical knowledge, creativity, and environmental responsibility.

5.1 PEDAGOGICAL DIMENSION OF THE PROCESS

The dynamic of constant support from teachers/tutors shaped a learning model based on research as an experience, in which error, observation, and critical review became pedagogical tools. Thus, the methodology not only enabled valid technical results to be achieved but also consolidated a deep understanding of the process of designing sustainable materials as a scientific practice within the academic context.

5.2 LIMITATIONS AND SCOPE

Like any experimental research process, this study has limitations that must be considered in its interpretation. These include the small sample size and the lack of long-term durability testing, factors that limit the extrapolation of results to an industrial scale. Also, the seasonal availability of the residue and the variability in the chemical composition of E. globulus could influence the consistency of the material.

However, these limitations open up future lines of research. It is suggested that studies be expanded to include thermal optimization processes, the use of natural additives that improve material stability, and the exploration of structural applications. At the same time, educational experience shows that integrating design, science, and teaching is an effective strategy for developing research skills and strengthening design education from a sustainable perspective.

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