

EXPLORATION OF EGGHELLS WASTE AS A SUSTAINABLE INTERIOR MATERIAL THROUGH MATERIAL-DRIVEN DESIGN (MDD)

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Abstract

Food waste has become a pressing environmental issue within global sustainability discourse, yet it also holds significant potential as an alternative material resource. Among various food waste by-products, eggshell waste is abundant and rich in calcium carbonate, but remains largely underutilized in design contexts. Existing studies on eggshells predominantly focus on technical or performance based applications, leaving their experiential, aesthetic, and spatial potential underexplored. This study investigates the transformation of eggshell waste into a bio-based composite material for non-structural interior applications using the Material-Driven Design (MDD) framework. Adopting a practice-based design research approach, the study follows the full MDD sequence, encompassing material understanding, material characterization and experience, application vision, and material integration. Experimental exploration was conducted through variations in binder types, particle sizes, and mixing ratios, followed by surface finishing, color exploration, and tactile evaluation. The optimized material formulation was subsequently translated into a three-dimensional modular panel design and integrated with a lightweight metal framing system to examine its applicability within an interior context. The findings demonstrate that eggshell waste can be developed into a stable and expressive decorative surface material, where material behavior directly informs form, texture, and design decisions. By positioning eggshell waste as a design-active material, this research contributes to sustainable interior design discourse and highlights the relevance of Material-Driven Design as a methodology for transforming food waste into meaningful interior material applications.

Keywords: Eggshell Waste, Material-Driven Design, Sustainable Interior Design, Bio-based, Materials, Decorative Panels.

INTRODUCTION

Food waste has emerged as a critical environmental issue within global sustainability discourse, generating not only ecological burdens but also untapped material potential [1], [2]. Among various forms of food waste, eggshell waste represents a significant yet underutilized by-product produced daily by households, restaurants, and food-related industries [3]. Despite its high calcium carbonate content and distinctive granular texture, eggshell waste is most commonly disposed of as organic refuse or reused only in low-value applications [4]. Its potential as a bio-based material for interior design, particularly in relation to surface expression,

tactility, and aesthetic value, remains largely unexplored. Existing studies on eggshell waste have predominantly approached the material from technical and performance-oriented perspectives, such as its application in agriculture, biomedical fields, ceramics, or as filler material in construction composites [5], [6], [7]. While these studies contribute valuable insights into material strength, chemical composition, and durability, they often overlook how eggshell-based materials are perceived, experienced, and interpreted within spatial contexts. In interior environments, materials are not encountered merely as structural components but as surfaces that shape atmosphere, sensory engagement, and meaning [8], [9]. As such, the exploration of food-waste-derived materials for interior use requires a design-oriented framework that foregrounds material experience alongside material performance.

Interior design practice occupies a unique position in material innovation, as it bridges functional requirements with visual, tactile, and experiential qualities [10]. However, material development and interior design are frequently treated as separate domains, resulting in alternative materials being introduced into design processes only after their technical properties have been defined. This separation limits the role of designers in actively shaping material characteristics and restricts the exploration of waste-based materials to narrowly defined functional outcomes [11]. Addressing food waste within interior design therefore calls for an approach that allows material exploration, sensory evaluation, and design interpretation to evolve together. To respond to this challenge, this study adopts the Material-Driven Design (MDD) framework as a methodological foundation. MDD positions material exploration as a central driver of the design process, emphasizing iterative experimentation, material characterization, experiential evaluation, and application-oriented interpretation [12]. Rather than treating materials as passive inputs, MDD enables designers to engage with materials as evolving entities whose properties, behaviors, and meanings emerge through hands-on experimentation and reflection [13]. This approach is particularly relevant for waste-based materials, where material identity and value are not predefined but constructed through design processes.

This research presents the exploration of eggshell waste as a bio-based composite material for non-structural interior applications, following the entire sequence of the Material-Driven Design framework. The study begins with material understanding and characterization, examining binder selection, particle size variation, and mixing ratios. It then continues with experiential exploration through color application, surface finishing, and tactile assessment, before progressing toward form development and modular panel integration. The research does not aim to position eggshell-based composites as substitutes for structural building materials; instead, it focuses on their potential as decorative interior surfaces that communicate sustainability through material expression. By integrating food waste exploration with a material-driven design methodology, this study contributes to the discourse on

sustainable interior materials in three ways. First, it expands the understanding of eggshell waste beyond technical reuse by emphasizing experiential and aesthetic qualities. Second, it demonstrates the relevance of Material-Driven Design as a framework for transforming food waste into meaningful interior material applications. Third, it offers a design-oriented reference for future research on waste-based materials that seek to balance ecological responsibility with sensory and spatial value.

RESEARCH METHOD

Research Approach

This study adopts a practice-based design research approach, in which material experimentation and making function as the primary modes of inquiry. Practice-based research is commonly applied in art and design disciplines to generate knowledge through creative practice, where understanding emerges from iterative processes of making, testing, and reflective evaluation rather than hypothesis driven measurement alone [14], [15]. Within this framework, the research is structured using the Material-Driven Design (MDD) methodology. MDD positions materials not as passive components selected after design decisions, but as active drivers that shape design thinking through their properties, behaviors, and experiential qualities [12]. This approach is particularly relevant for waste-based materials, whose identity and value are not predefined but constructed through exploration and design interpretation.

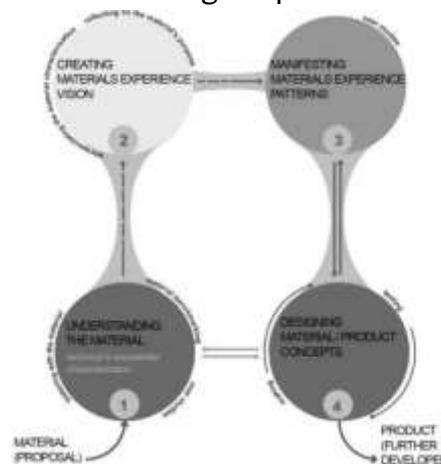


Figure 1. Material Driven Design Framework. Source: Karana et al., 2015.

The study follows the full sequence of the Material-Driven Design framework, consisting of material understanding, material characterization and experience, application vision, and material integration [12]. Rather than focusing on structural or engineering optimization, the research emphasizes material experience, surface qualities, and design potential for non-structural interior applications.

Research Setting and Material Source

All experiments were conducted independently in a domestic, non-laboratory setting using accessible tools and self-prepared materials. This setting reflects contemporary design practices that emphasize hands-on material exploration, low-tech experimentation, and designer-led material development [16]. Eggshell waste was collected from household food consumption and small-scale food sources. Prior to experimentation, the eggshells were thoroughly cleaned to remove residual membranes and biological contaminants, then dried either naturally or using a low-temperature oven. This preparation ensured material consistency while maintaining a low-impact and accessible processing method.

Material Preparation and Experimental Process

The experimental process was designed to systematically explore the material characteristics of eggshell based composites through controlled variations in processing methods and composition. Eggshell waste was collected from organic food sources and prepared through a multi step process to ensure material cleanliness and consistency. The collected eggshells were thoroughly washed to remove residual membranes and biological contaminants, then dried either naturally or in an oven at approximately 60°C. Drying was conducted to prevent contamination and to stabilize the material prior to further processing. Once dried, the eggshells were mechanically crushed and sieved to obtain different particle sizes, ranging from coarse fragments to fine powder. These variations were intended to examine the influence of particle size on surface texture, density, and visual appearance. To evaluate the role of binding agents in shaping material behavior, three different binders were selected: white cement, polyvinyl acetate (PVAc) glue, and tapioca flour. These binders were chosen to represent differing material characteristics, including industrial versus bio-based properties, rigidity versus flexibility, and varying degrees of environmental impact. A consistent base mixing ratio of binder to eggshell at 1:3 was initially applied to allow comparative observation across samples. The eggshell binder mixtures were cast into silicone molds measuring 10 × 10 cm with thicknesses of 1 cm or 2 cm, forming panel like samples suitable for surface evaluation. Drying was conducted either through natural air drying or oven drying, depending on the experimental condition. After demolding, samples were allowed to cure gradually to minimize cracking and deformation. This stage corresponds to the material understanding and initial material characterization phases of the MDD framework.

Binder, Particle Size, and Mixing Ratio Exploration

Following the initial binder comparison, further experiments were conducted to refine material stability and surface quality. Particle size variations were explored by comparing samples made from coarse eggshell powder and fine eggshell powder,

using the same binder ratio. These tests aimed to observe differences in surface homogeneity, porosity, and tactile perception. Subsequently, mixing ratio experiments were carried out to identify compositions that offered greater material stability for interior surface applications. Two ratios 50:50 and 30:70 (binder to eggshell) were tested to evaluate their influence on cracking behavior, density, and overall material cohesion. Observations were recorded after drying and during short-term handling to assess surface durability and resistance to minor pressure. These experiments were not intended to determine structural performance but to identify compositions that demonstrate sufficient stability, visual consistency, and tactile quality for non-structural interior use. This stage represents the material characterization and experience phase of the MDD framework.

Surface Finishing and Color Exploration

To further investigate material experience, surface finishing and color treatments were introduced as part of the experimental process. Once the samples had fully cured, selected panels were polished using sandpaper to expose embedded eggshell fragments, producing a terrazzo like visual effect. This finishing process allowed the evaluation of surface smoothness, fragment visibility, and aesthetic consistency. Color exploration was conducted using two approaches: natural dye and synthetic dye. For the natural dye, calendula (marigold flower) powder was heated with water and apple cider vinegar to create a concentrated solution, which was then mixed into the eggshell composite. For comparison, commercially available liquid food coloring was used as a synthetic dye and added directly to the mixture until the desired color intensity was achieved. Both colored mixtures were molded into 10 × 10 × 2 cm panels and oven dried at approximately 100°C for three hours. Post-drying observations focused on color intensity, uniformity, surface texture, and changes after short-term exposure to handling and moisture. This stage further extends the material experience exploration within the MDD process.

Application Vision: 3D Panel Design and Material Integration

Following material characterization and experiential evaluation, the research progressed to the application vision stage of the Material-Driven Design framework. At this stage, the optimized eggshell-based composite material was translated into a three-dimensional panel design to explore its potential as a modular interior surface element. The 3D panel design was developed based on observed material behavior, including thickness limitations, edge stability, surface texture, and curing performance. These material constraints informed decisions regarding panel dimensions, geometry, and modular configuration. The panel was conceived as a non-structural, decorative component intended for wall surface applications. To evaluate material integration, selected panels were combined with lightweight metal framing

fabricated by a metalworker. This integration tested drilling resistance, edge integrity, and compatibility between the eggshell-based composite and metal structural elements. The process corresponds to both the application vision and material integration stages of MDD, where material behavior is examined in relation to potential design contexts rather than isolated material properties [12].

Evaluation Criteria and Data Collection

Data collection relied on qualitative and experiential evaluation, consistent with design-oriented material research [15], [17]. Evaluation criteria included surface texture, porosity, color expression, bonding behavior, perceived strength during handling, resistance to light pressure, and tactile and visual qualities. Observations were documented through written notes and photographic records. Rather than conducting standardized mechanical testing, the study prioritizes material behavior and experiential qualities relevant to non-structural interior surface applications.

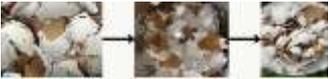
Scope and Limitations

This research does not aim to assess structural performance or long-term durability under architectural load conditions. The experiments are exploratory in nature and conducted at a small scale. The findings are intended to reveal material potential and design relevance rather than to provide engineering validation, serving as a foundation for further design development and future research.

RESULT AND DISCUSSION

This section presents and discusses the results of the material exploration process conducted through the Material-Driven Design (MDD) framework. The discussion follows the sequential stages of MDD, beginning with material characterization and experiential evaluation, and progressing toward application vision and material integration through three-dimensional panel design. The aim of this section is not to validate eggshell-based composites through engineering performance, but to reveal their material behavior, experiential qualities, and design potential for non-structural interior applications. All material experiments were conducted following the general procedure outlined below.

Table 1. Experimental Procedures

Experimental Procedures		
Stage	Illustration	Procedures
1		<p>Cleaning & Drying</p> <p>Eggshells are collected from organic sources and thoroughly washed to remove any remaining membranes or biological residues. After cleaning, the shells are dried either naturally or in an oven at approximately 60°C to prevent contamination and facilitate the subsequent processing steps.</p>
2		<p>Crushing & Sieving</p> <p>The dried eggshells are crushed using a grinder until they become small fragments or are processed into a fine powder. The particle size is adjusted according to the desired final outcome.</p>
3		<p>Mixing with Binders (White Cement, PVAc Glue, and Tapioca)</p> <p>The crushed eggshells are then mixed with binders such as white cement or natural alternative binders like egg white or limewater. A commonly used ratio in laboratory studies is 70% eggshell fragments and 30% cement (Vasudevan et al., 2020).</p>
4		<p>Molding and Drying</p> <p>The mixture is poured into silicone molds measuring 10 × 10 × 1 cm, or alternatively 10 × 10 ×</p>

Experimental Procedures		
Stage	Illustration	Procedures
	 ↓ Option 1 (Oven Drying)  Option 2 (Natural Drying) 	2 cm, to form the panels. After molding, the material is left to dry for 24–48 hours at room temperature or oven-dried. Once removed from the mold, the panels are further dried gradually to ensure optimal curing.

Polishing and Finishing		
5	 	After the material has hardened, its surface is polished using sandpaper to reveal the embedded eggshell fragments, creating a visual effect similar to conventional terrazzo. This process also smooths the surface to make it suitable for use as a decorative interior material.

Source: Personal Analysis (2025)

Material Characterization: Binder, Particle Size, and Mixing Ratio

Binder Selection

The first experiment focused on evaluating the performance of three different binders white cement, tapioca flour, and polyvinyl acetate (PVAc) glue combined with fine eggshell powder at a consistent ratio of 1:3 (binder to eggshell). All samples were molded into panels measuring 10 × 10 × 1 cm and dried for 48 hours.

Table 2. Experimental Procedures

Experimental Procedures			
Aspect	White Cement	PVAc Glue	Tapioca Flour
Experiment Date	 Date: 02/06/25	 Date: 02/06/25	 Date: 02/06/25

Experimental Procedures			
Aspect	White Cement	PVAc Glue	Tapioca Flour
Sample Code	B1	B2	B3
Mix Ratio (Binder: Eggshell)	1:3	1:3	1:3
Dimensions	10 cm x10 cm x 1 cm	10 cm x10 cm x 1 cm	10 cm x10 cm x 1 cm
Environmental Friendliness	Moderate (emissive)	High (biodegradable)	Moderate (non-biodegradable)
Surface Color	Snow white	Ivory white	Brownish white
Bonding Strength	Strong but rigid	Strong and flexible	Soft, easily crumbled
Durability	Long-lasting	Stable	Not long-lasting
Drying Time	48 hours	48 hours	48 hours
Testing	Does not crack when held or lightly tapped; withstands finger pressure but is heavy	Stable after drying; no cracking; remains intact after hand-grip and light-drop tests	Deforms after 3 days; fine surface cracks; easily crumbles when pressed
Notes	Not very eco-friendly, less natural appearance	Eco-friendly, smooth and homogeneous texture	Undergoes shape changes after 3 days

Source: Personal Analysis (2025)

The results indicate clear differences in material behavior across binders. White cement produced panels with high rigidity and structural strength; however, the material appeared heavy, less flexible, and exhibited a relatively industrial visual character. Additionally, its environmental impact was considered less favorable due to cement-related emissions. Tapioca flour, while biodegradable and environmentally friendly, resulted in panels that were mechanically unstable, prone to deformation, and susceptible to cracking after several days of drying.

In contrast, PVAc glue demonstrated the most balanced performance. Panels bonded with PVAc exhibited stable adhesion, flexible behavior, and a homogeneous surface texture. The material remained intact after handling tests, including light pressure and minor drops, without visible cracking or deformation. Based on these observations, PVAc was selected as the primary binder for subsequent experiments

Eggshell Particle Size Evaluation

The second stage examined the influence of eggshell particle size on material performance using the selected PVAc binder at a 1:3 ratio. Two particle sizes were tested: coarse powder and fine powder.

Table 3. Experimental Procedures

Aspect	Coarse Powder	Fine Powder
Experiment Date	 Date: 01/10/25	 Date: 01/10/25
Sample Code	P1	P2
Mix Ratio (Binder: Eggshell)	1:3	1:3
Dimensions	10 cm x10 cm x 1 cm	10 cm x10 cm x 1 cm
Surface Color	Brownish White	Greyish White
Texture & Porosity	Strong, does not crack under pressure but feels fragile at the edges; resistant to water for a short duration	Does not crack under pressure; surface remains stable; resistant to short-term water exposure without deformation
Strength & Adhesion	Low adhesion, uneven surface	Homogeneous and denser surface
Testing	Does not crack when held or lightly tapped; withstands finger pressure but is heavy	Stable after drying; no cracking; remains intact after hand-grip and light-drop tests
Notes	Not very eco-friendly, less natural appearance	Eco-friendly, smooth and homogeneous texture

Source: Personal Analysis (2025)

Panels produced with coarse eggshell particles showed a rougher surface texture, higher porosity, and lower edge stability. Although the samples did not immediately crack under pressure, the material felt fragile, particularly along the edges. Conversely, fine eggshell powder resulted in denser, more compact panels with smaller pores and a smoother, more homogeneous surface. The finer particle distribution allowed better binder penetration and improved inter-particle adhesion. These findings suggest that fine eggshell powder is more suitable for decorative interior panel applications, as it offers improved surface quality, cohesion, and tactile consistency.

Mixing Ratio Optimization

Following particle size selection, two binder-to-eggshell ratios were evaluated: 50:50 and 30:70 (PVAc to fine eggshell powder). Both compositions were molded into 10 × 10 × 1 cm panels and subjected to drying and handling tests.

Table 4. Experimental Procedures

Aspect	Ratio 1	Ratio 2
Experiment Date	 Date: 08/10/25	 Date: 08/10/25
Sample Code	R1	R2
Mix Ratio (Binder: Eggshell)	50:50	30:70
Dimensions	10 cm x10 cm x 1 cm	10 cm x10 cm x 1 cm
Surface Color	Brownish White	Greyish White
Texture & Porosity	Cracked, small pores	Dense, small pores
Strength & Adhesion	Moderately strong	Strong
Testing	Develops fine cracks after drying; less water-resistant; lighter in weight	Shows no cracking; withstands light pressure; structure is more solid and stable
Notes	Lightweight, easily cracked	Not easily cracked, stable after drying

Source: Personal Analysis (2025)

The 50:50 ratio produced lighter panels but exhibited micro-cracks after drying and reduced resistance to moisture exposure. In contrast, the 30:70 composition demonstrated superior stability, with no visible cracking, improved density, and stronger resistance to light pressure. Despite the reduced binder content, adhesion remained effective due to the fine particle size, resulting in a solid and visually consistent material. Overall, the 30:70 PVAc-to-eggshell ratio was identified as the optimal formulation, balancing mechanical stability, material cohesion, and natural visual expression. Summary of Experiment 1 Findings:

- a. Optimal binder : PVAc glue
- b. Optimal Particle size : Fine eggshell powder
- c. Optimal ratio : 30:70 (PVAc : eggshell)

This formulation was subsequently used as the base material for color and form exploration.

Color Exploration

Table 5. Experimental Procedures

Experimental Procedures		
Stage	Illustration	Procedures
1		<p>Preparation of the Base Mixture</p> <p>Preparing two groups of material mixtures using the best base composition from the previous experiments, namely a ratio of PVAc glue to eggshell powder of 30 : 70 (fine powder).</p>
2		<p>Natural Dye W1</p> <p>Calendula powder (marigold flower) is heated together with water and apple cider vinegar in a ratio of 1 : 2 : 0.5 for approximately 5 minutes until it forms a concentrated solution, which is then mixed into the eggshell compound.</p>
3		<p>Synthetic Dye (W2)</p> <p>Liquid food coloring (Koepoe Koepoe brand) is added directly to the mixture until the desired color intensity is reached, then stirred until homogeneous.</p>
4		<p>Molding</p> <p>The mixture is poured into a 10 cm x 10 cm x 2 cm panel mold.</p>
5		<p>Drying Process</p> <p>The panels are dried in an oven at a temperature of 100°C for approximately 3 hours</p>
6		<p>Observation of Results</p> <p>After drying, observations were conducted to assess color intensity, uniformity, post-drying color changes, and surface texture.</p>

Source: Personal Analysis (2025)

Natural and Synthetic Dye Application

The second experimental phase investigated color application using two different dye approaches: a natural dye derived from calendula (marigold flower) and a synthetic food-grade dye. Both dyes were applied to the optimal base formulation (PVAc : eggshell = 30:70, fine powder) and molded into 10 × 10 × 2 cm panels, followed by oven drying at approximately 100°C for three hours.

Table 6. Experimental Procedures

Aspect	Natural Dye	Synthetic Dye
Experiment Date	 Date : 16/10/25	 Date : 16/10/25
Sample Code	W1	W2
Mixing Method	Calendula powder is heated with water and apple cider vinegar (1:2:0.5) for approximately 5 minutes until a concentrated solution is formed, then mixed into the eggshell powder mixture.	Liquid food coloring is added directly to the mixture and stirred until homogeneous.
Dimensions	10 cm x10 cm x 2 cm	10 cm x10 cm x 2 cm
Surface Color	Naturally uneven (gradated)	Fairly even
Texture & Porosity	Smooth, slightly porous	Smooth, slightly porous
Stability of Color	Stable, but the color fades slightly	Highly stable
Testing	After 48 hours of drying, the natural calendula color appears softer and shows slight fading due to natural oxidation. No changes in texture were observed. It remains water-resistant for a short period without any deformation.	After 48 hours, the synthetic color remains bright and homogeneous with no visible changes; the surface stays smooth and dense. It is water-resistant for a short duration without any deformation.
Notes	Soft and natural color, giving an organic impression that supports the sustainability	A strong and appealing color that still highlights the natural character of the reused

Aspect	Natural Dye	Synthetic Dye
	narrative.	material.

Source: *Personal Analysis (2025)*

The natural calendula dye produced soft, warm color tones with organic gradation. However, color distribution was less uniform due to incomplete dispersion of pigment particles, resulting in subtle variations across the surface. After drying and 48 hours of exposure at room temperature, the color showed slight fading, attributed to natural oxidation processes. Despite this, surface texture and structural integrity remained stable. The synthetic dye, on the other hand, yielded brighter and more uniform coloration. The pigment dispersed evenly throughout the mixture, producing consistent visual results and higher color stability after drying and handling tests. No significant changes in texture or material cohesion were observed. These results indicate that natural dyes contribute to an organic, handcrafted aesthetic aligned with sustainability narratives, while synthetic dyes offer superior control in terms of color intensity and uniformity.

Application Vision: 3D Panel Design

Building upon the optimized material formulation and surface treatments, the research progressed to the application vision stage of the MDD framework through the development of a three-dimensional panel design. The application vision focused on translating material behavior into a modular panel system suitable for non-structural wall surfaces.

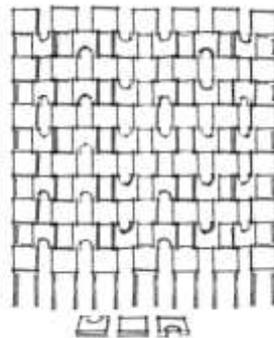


Figure 2. Preliminary Design Sketch. Source: *Personal Documentation 2025*.

The 3D panel design was informed directly by observed material constraints, including thickness limitations, edge stability, and surface behavior. These constraints guided decisions regarding panel dimensions, geometry, and modular configuration. The resulting design emphasized simplicity and repeatability, allowing the material texture to remain the primary visual element.



Figure 3. 3D Design. Source: Personal Documentation 2025.

By positioning the panel as a modular surface component, the design accommodates variation in material appearance while enabling systematic installation. This approach reflects a material-led design logic, where form emerges from material properties rather than being imposed externally.

Material Integration and Modular System

The final stage of the exploration involved integrating the eggshell-based panels into a modular system using lightweight metal framing. This integration tested the compatibility between the bio-based composite material and an industrial structural element.

Table 7. Experimental Procedures

Activities	Illustration	Description
Panel Sample Selection		<p>Selecting the best-performing panels from the color exploration experiment (W1 and W2) to be used as test samples for final form development.</p>
Surface Refinement		<p>The selected panels were processed by a professional carpenter using a mechanical sanding machine to achieve smoother and more even surfaces across all sides. At this stage, slight color fading was observed, particularly in naturally dyed panels. Additionally, embedded eggshell fragments became more visible on the surface, contributing to a new visual character that appeared more organic and tactile.</p>

Activities	Illustration	Description
Modular Form Refinement		<p>The refined panels were adjusted to ensure uniform dimensions and precise 90-degree angles, facilitating modular assembly. This process resulted in panels with consistent thickness and improved geometric accuracy.</p>
Structural Integration Test		<p>The panels were arranged adjacently and connected using a lightweight metal frame fabricated by a metalworker to form a unified wall panel system. This test aimed to evaluate the compatibility between the natural eggshell-based panels and metal structural elements. The results indicate that the panels were sufficiently strong to withstand drilling during metal fastening without cracking or disintegration, demonstrating adequate material density and bonding for lightweight interior applications.</p>
Result Observation		<p>Observations focused on form consistency, joint precision, and the visual integration between the natural material texture and the metal structure. The results show that the panels appear more refined and structurally cohesive, despite minor color changes caused by surface sanding. The increased visibility of eggshell fragments further enhances the material's sustainable character and natural material expression.</p>

Source: Personal Analysis (2025)



Figure 4. Modul Eggshell Panel. Source: Personal Documentation 2025.

The panels demonstrated sufficient resistance to drilling and fastening, with no significant cracking or fragmentation observed during assembly. The combination of eggshell panels and metal framing created a visual contrast between natural and industrial materials, reinforcing the material narrative of reuse and transformation. From an experiential perspective, the system conveyed both material honesty and structural clarity, suggesting potential applicability within contemporary interior contexts. This stage confirms that the developed material is not only viable as an isolated sample but also capable of functioning as part of a larger interior system. The integration process thus completes the MDD sequence by translating material exploration into a design-relevant application.

Discussion

The results of this study demonstrate that eggshell waste can be effectively transformed into a non-structural interior material through a Material-Driven Design (MDD) approach, in which material exploration functions as the primary driver of design development. Rather than optimizing the material for structural or engineering performance, the research foregrounds material experience, revealing how variations in binder type, particle size, mixing ratio, and surface finishing directly influence visual appearance, tactile quality, and perceived material value. This orientation aligns with theories of materials experience, which emphasize that materials in interior contexts are primarily encountered through sensory perception rather than technical performance alone [8], [11], [17]. The selection of PVAc glue combined with fine eggshell powder at a 30:70 ratio can be explained through composite material principles, where binder flexibility and uniform particle distribution enhance surface cohesion and stability [10]. Fine particles allow more effective binder penetration, producing denser and more homogeneous surfaces. While previous studies on eggshell composites focus largely on mechanical strength and durability [5],[7], this

research extends the discussion by interpreting material behavior from a design oriented and experiential perspective, relevant to interior surface applications. From an experiential standpoint, surface texture, chromatic variation, and tactile response play a central role in the material's interior suitability. As noted by Pallasmaa and Zumthor, materials contribute to spatial atmosphere through sensory perception and emotional resonance [8], [9]. The visible eggshell fragments and subtle surface irregularities support notions of material honesty, allowing the panels to communicate their origin as reused food waste rather than concealing it [11]. In the color exploration, naturally dyed samples exhibited variation and softness, while synthetic dyes produced more uniform results. Such variation can be understood through Ingold's concept of making, where material qualities emerge through process, and Pye's notion of workmanship of risk, in which imperfection contributes to aesthetic value rather than detracting from it [18], [19]. The application of the Material-Driven Design framework proved critical in enabling these outcomes. MDD allows material identity and meaning to emerge through iterative experimentation and reflection, particularly when working with waste-based materials whose value is not predefined [12], [13], [16]. In this study, material behavior directly informed design decisions from formulation to modular panel geometry, challenging linear design workflows that treat materials as passive inputs [11]. The development of a three dimensional modular panel demonstrates that material driven research can extend beyond laboratory samples into design relevant artifacts without full spatial simulation. By translating material constraints such as thickness and edge stability into modular form, the research aligns with contemporary interior design practices that prioritize material authenticity and sustainability narratives [9], [10]. Integration with lightweight metal framing further confirms the material's applicability as a decorative wall surface.

Despite its contributions, the study remains exploratory. Future research may investigate long-term durability, moisture resistance, and aging behavior, as well as larger-scale production and application within specific interior contexts. From a sustainability perspective, further exploration of localized sourcing and circular production systems could strengthen the ecological narrative of food waste based interior materials [1], [2], [20]. Overall, this research reframes eggshell waste as a design-active material, offering a material-driven model that balances ecological responsibility with experiential and spatial value.

CONCLUSION

This study demonstrates that eggshell waste can be transformed into a viable non-structural interior material through a Material-Driven Design (MDD) approach that emphasizes material exploration, experiential evaluation, and design-led interpretation. By adopting a practice-based design research methodology, the research positions material experimentation not merely as a technical process, but as

a critical generator of design knowledge. Through systematic exploration of binder types, particle sizes, and mixing ratios, the study identifies an optimal material formulation using PVAc glue with fine eggshell powder at a 30:70 ratio, which provides a balance between material stability, surface consistency, and visual authenticity. Surface finishing and color exploration further reveal how experiential qualities such as tactility, texture, and visual depth can be articulated through design interventions, highlighting the importance of material experience in interior applications. The translation of the optimized material into a three-dimensional modular panel design marks a key contribution of this research. Rather than presenting a speculative spatial design, the study demonstrates how material behavior can directly inform form, geometry, and modular logic at the component level. The successful integration of eggshell-based panels with lightweight metal framing confirms the material's applicability within a practical interior system, reinforcing its potential as a decorative wall surface.

From a broader perspective, this research contributes to sustainable interior design discourse by reframing food waste specifically eggshell waste as a design-active material rather than a passive by-product. The use of the Material-Driven Design framework proves effective in bridging material experimentation and design application, offering a replicable model for exploring other waste-based materials within design contexts. While the study is exploratory and limited to small-scale, non-structural applications, its findings provide a material-centered foundation for future research. Further studies may extend this work through long-term durability testing, larger-scale production, or integration into specific spatial contexts. Ultimately, this research underscores the role of designers in shaping sustainable material futures by transforming waste into meaningful interior expressions through material-led creativity.

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