An Embodied Carbon Life Cycle Assessment (LCA) for Earthen and Bio-Based Finishing Systems in Residential Interior

Tarun L, Dr. Nischay N
Department of Interior Design, JD School of Design, Bengaluru, Karnataka, India.,
Associate Head, Department of Interior Design, JD School of Design, Bengaluru, Karnataka, India.
nischay.n@jdinstitute.edu.in

***Abstract*—This study examines how interior material finish characteristics—specifically Embodied Carbon (EC) and moisture permeability—affect the total environmental performance of earthen residential interiors, focusing on the Indian context. Initial observations revealed a recurrent disconnect where low-carbon earthen structures (Rammed Earth, CSEB) were frequently finished with high-EC, synthetic materials (e.g., vitrified tiles, acrylic distempers). The research problem is the lack of empirical evaluation and quantitative, design-oriented metrics linking interior finish properties to total Life Cycle Carbon (LCC) and breathability performance. A quantitative survey indicated that, despite an awareness of EC, designers are primarily deterred from using low-carbon, bio-based alternatives (like clay or lime plasters) by performance anxieties, namely concerns over long-term durability and maintenance requirements (68.4% concern). The study posits that bio-based and breathable finishes reduce the total embodied carbon of the interior system and improve the functional performance (hygrothermal stability and wall health) of earthen construction. All hypotheses are designed to be testable using LCA databases for kg CO2e and scientific metrics like the vapor diffusion resistance factor (mu) and Moisture Buffering Values (MBV). The final objective is to propose a "Regenerative Interior Specification Guide" supported by measurable data to bridge the specification gap driven by risk aversion.**

Index Terms—Embodied Carbon; Earthen Construction; Life Cycle Assessment; Bio-based Finishes; Moisture Permeability; Regenerative Design; Moisture Permeability; Clay and Lime Plasters; Bio-based Interior Finishes; Sustainable Materials; Environmental Building Assessment; Moisture Buffering Value (MBV);

I. Introduction

The global construction industry faces a continuous challenge in minimizing its significant carbon footprint. While the benefits of low-carbon structural systems, such as Rammed Earth and **Compressed Stabilized Earth Blocks (CSEB)**, are widely cited in literature, attention is often restricted to the building envelope. Initial observations across contemporary residential mud houses and "eco-resorts" revealed a critical specification failure: low-carbon structures are frequently finished with high-impact materials that reintroduce high levels of **Embodied Carbon (EC)** and toxicity. Examples of high-impact specifications include Vitrified/Porcelain tiles (high-heat manufacturing), PVC-based skirting, Acrylic Distempers, and Gypsum false ceilings.

Designers often prioritize perceived durability and "cleanliness" associated with industrial finishes, overlooking the energy intensity of their production, particularly high-temperature kiln firing. This highlights a critical disconnect between the aesthetic perception of a material and its real carbon cost (see Figure 1). The highest carbon spikes typically occur in wet areas (bathrooms/kitchens) and flooring, where high-EC ceramics and cementitious composites are the default standards. The environmental impact is most critical during the "Production" (A1-A3) and "Replacement" (B4) life cycle stages, which are amplified by short-lifespan trends (Simonen, DeWolf, & Slessor, 2022).

Conversely, traditional or bio-based finishes—such as Red Oxide (IPS) flooring, Lime-Araish plasters, and Casein paints—offer seamless aesthetic integration and superior thermal and hygrothermal performance (Minke & Wangelin, 2009). Non-breathable finishes trap moisture within earthen walls, leading to structural degradation and reduced air quality, while breathable, regenerative finishes promote wall health and can sequester carbon.

The literature review identified a substantial gap: existing studies predominantly focus on the structural benefits (Arrigoni, Daniotti, & Dotelli, 2021) or commercial office interiors, lacking specific, quantitative EC data for interior finishes in residential earthen contexts. This research addresses this gap by establishing quantitative relationships between interior specifications (IV: EC and moisture permeability) and the overall performance of earthen construction (DV: Total EC and wall health).

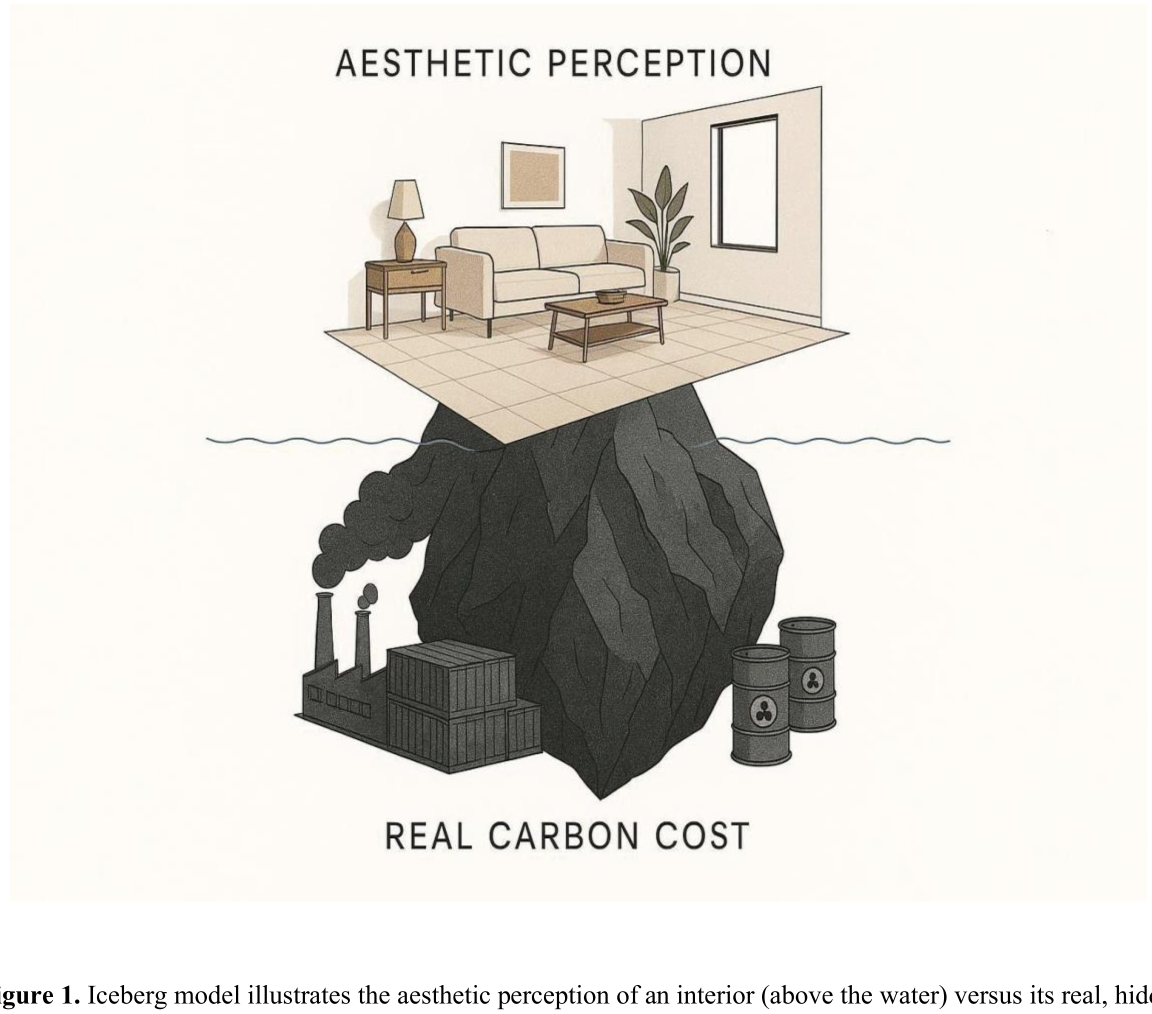


Figure 1. Iceberg model illustrates the aesthetic perception of an interior (above the water) versus its real, hidden carbon cost, encompassing manufacturing plants and synthetic components (below the water).

II. Material and Methods

1) Research Design and Problem Definition

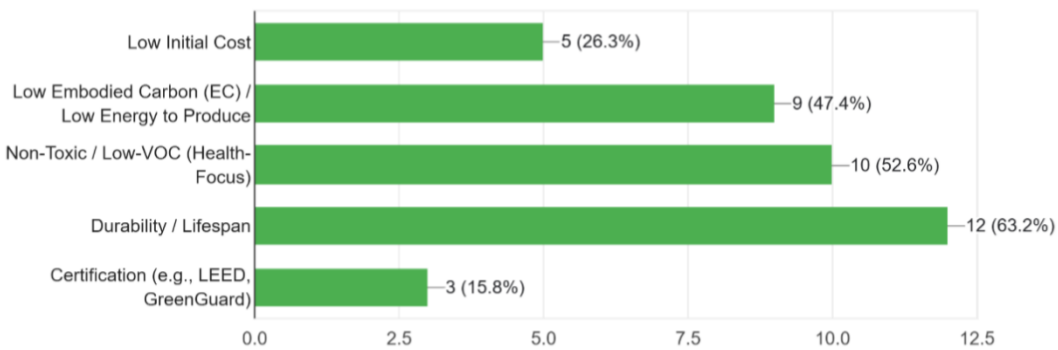
This study employed an explanatory mixed-methods approach, combining initial observations with quantitative designer surveys and a theoretical Life Cycle Assessment (LCA) framework. The research is centered on the **Problem Statement**: Existing research offers limited empirical evaluation of the specific material finish properties that influence the Total Life Cycle Carbon of earthen interiors. The goal is to move beyond qualitative principles like "local sourcing" to establish quantitative EC metrics.

2) Survey Methodology
A cross-sectional **quantitative survey** was employed to assess the perceptions, motivations, and specification barriers among interior design professionals and homeowners with experience in sustainable and vernacular building projects. This methodology provided the necessary behavioral and attitudinal data to contextualize the LCA.

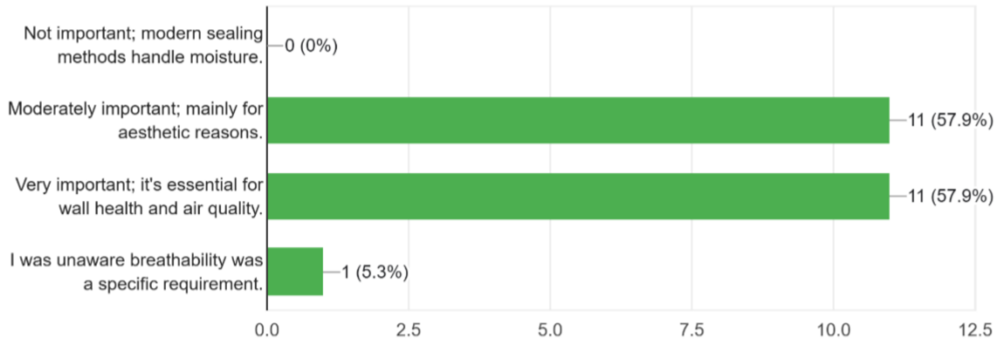
- **Sample:** The survey was administered electronically, yielding **responses** from practicing designers and clients across India who engage with low-carbon building materials (e.g., Rammed Earth, CSEB).

- **Instrument:** The questionnaire consisted of **eleven closed-ended questions** and was structured into five key thematic areas designed to capture both knowledge and behavioral data:

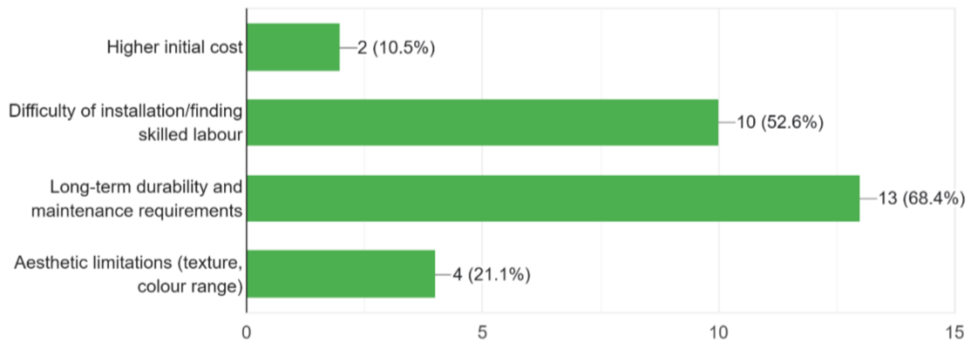
    - ❖ **Defining Sustainability:** Assessing which factors (**EC, durability, non-toxicity**) are prioritized in material selection (Q1).



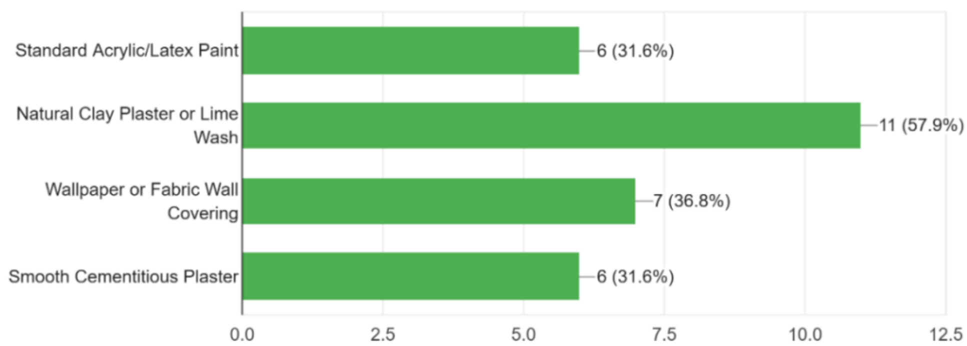
- **Carbon Literacy:** Identifying perceived high-impact contributors (e.g., high-heat manufacturing vs. transport distance) and reported usage of environmental data (EPDs/LCA) (Q2, Q5).



- **Material Preference and Barriers:** Determining preferred material choices for general vs. wet areas and ranking the primary factors deterring the adoption of bio-based materials (e.g., cost, durability, maintenance) (Q4, Q8).



- **Functional Performance:** Evaluating the understanding of finish compatibility with earthen walls, specifically the importance of **moisture permeability** for wall health and air quality (Q6).



- **Analysis:** The collected data was analyzed using descriptive statistics (percentages, means) to quantify professional consensus and identify high-impact specification inertia, directly informing the parameters and scenarios for the subsequent comparative LCA framework.

3) Proposed Hypotheses and Testability

The study's testable hypotheses predict a relationship between finish properties and performance, forming the basis for the comparative LCA simulation phase.

Independent Variable (IV): Interior material finish characteristics, specifically: Embodied Carbon kg CO2, Moisture permeability / breathability, Manufacturing energy intensity, and Chemical composition (bio-based vs. synthetic).

Dependent Variable (DV): Environmental and functional performance of earthen residential interiors, measured through: Total Embodied Carbon of the interior system (LCA values), Hygrothermal performance (moisture buffering, vapor permeability), Interior air quality outcomes, and Long-term durability and maintenance cycles.

Declarative Hypotheses:

- Bio-based and breathable finishes (clay, lime, casein) significantly reduce the total embodied carbon of earthen interiors compared to high-energy industrial finishes.
- Higher moisture permeability in interior finishes improves the hygrothermal stability and wall health of earthen construction, thereby extending the structure's lifespan.

Testability: All variables are testable. EC values can be measured as kg CO2e\m^2 using LCA databases. Moisture permeability is measurable through the vapor diffusion resistance factor (mu) and Moisture Buffering Values (MBV). Durability is measurable through maintenance and replacement cycles.

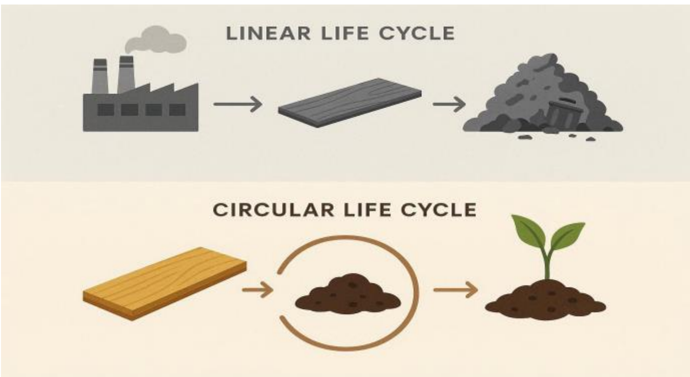


Figure 2. Diagram comparing the **Linear Life Cycle** (production, use, disposal) of conventional materials with the **Circular Life Cycle** (regenerative material use, reuse, and natural return to earth) supported by bio-based materials.

III. Results and Discussion

The analysis of the designer survey confirmed the central conflict between low-carbon goals and specification choices.

1) Specification Inertia in High-Risk Zones

The key finding is the prioritization of longevity over initial carbon metrics.

- Durability as Sustainability: The leading factor defining sustainability was "Durability/Lifespan" (63.2%), surpassing "Non-Toxic/Low-VOC" (52.6%) and "Low Embodied Carbon" (47.4%).
- Performance Anxiety Barrier: The primary barrier to using low-carbon alternatives was concerns regarding "Long-term durability and maintenance" (68.4%), significantly higher than "Higher initial cost" (10.5%). This risk aversion pushes designers toward conventional, high-carbon materials despite higher initial costs not being the main deterrent.

2) Hygrothermal and Durability Implications

Despite a strong alignment of preference for chemically compatible finishes like "Natural Clay Plaster or Lime Wash" (57.9%) for general walls, functional certainty drives high-carbon choices in wet areas.

- Wet Area Rejection: "Standard Glazed Porcelain or Ceramic Tile" remains the top choice (47.4%) for wet areas. The leading cause for rejecting natural/earthen-compatible materials is "Concerns about water or abrasion damage" (52.6%).
- Carbon Literacy: Respondents generally possess a high level of carbon literacy, correctly identifying "High-heat/energy used during manufacturing" (57.9%) as the biggest contributor to embodied carbon, outweighing transport distance (36.8%).

3) Hygrothermal and Durability Implications

The functional properties of finishes are critical for earthen construction.

- **Moisture Compatibility:** Respondents placed equal importance (57.9% each) on breathability for "wall health and air quality" and for "aesthetic reasons". Non-breathable finishes trap moisture, leading to degradation, whereas natural plasters "breathe," promoting wall health and mold prevention (Minke & Wangelin, 2009).
- **Repairability:** Natural clay and lime plasters offer superior long-term durability and are often easier to repair (e.g., buffed out with a damp sponge) than synthetic paints, which require frequent repainting, increasing the long-term carbon footprint (Simonen, DeWolf, & Slessor, 2022).

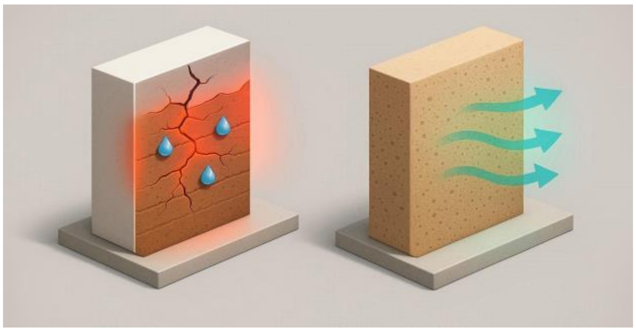


Figure 3. Comparative illustration showing the difference between a non-breathable wall finish (left) where moisture is trapped, leading to cracks, and a breathable wall finish (right) which permits vapor exchange, ensuring wall health and air quality.

IV. Conclusion

The survey confirms the central research problem: interior finishes frequently reintroduce high levels of embodied carbon into otherwise low-carbon structures. This is driven by a **specification gap** resulting from **risk aversion** and a critical lack of quantifiable, empirically-validated performance data for bio-based alternatives regarding long-term durability and maintenance.

The study’s hypotheses are testable and positioned to provide the necessary quantitative data to address these concerns. Future research must focus on providing measurable, verified data, such as comparative EC (LCA) and moisture performance metrics, to enable designers to overcome the performance anxiety associated with natural finishes. This research will benefit the architectural and design community by providing data-driven specification guidance, ensuring that the environmental integrity of the low-carbon structure is maintained through the choice of regenerative interior finishes, reducing the total life-cycle carbon footprint of the residential environment.

V. Acknowledgment

References

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