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Eco-Friendly Architecture for the Tropics: A Comparative Study of Sustainable, Low-Cost Housing Using CSEB, Bamboo and Fly Ash Bricks

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Abstract

The residential building sector is responsible for a substantial share of global energy consumption and CO_2 emissions, driven largely by resource-intensive materials such as reinforced cement concrete (RCC) and fired clay bricks. At the same time, many households in tropical regions struggle with escalating construction costs and poor thermal comfort, leading to increased reliance on mechanical cooling. This paper presents a comparative design and simulation study of a designing single family housing unit that replaces conventional RCC and fired clay brick construction with a low-energy, high-mass material palette compressed stabilized earth blocks (CSEB) for walls, bamboo for primary structure, and fly ash bricks for internal partitions.

Using cradle to gate embodied energy estimation and dynamic thermal performance simulation for a typical peak summer day (outdoor maximum 40 °C); the proposed design is compared against a conventional RCC fired brick baseline of similar size and spatial programme. Results indicate that the sustainable scheme can achieve approximately 70% reduction in embodied carbon and about 22% reduction in construction cost, primarily by substituting high-impact materials and eliminating plaster and paint through exposed CSEB finishes. Thermal simulations show that the proposed unit maintains indoor temperatures up to 9 °C cooler than the outdoor peak, largely through orientation, buffer zones, stack-effect ventilation, and high thermal-mass walls.

The findings are discussed against recent literature on CSEB performance, bamboo as a structural material, fly ash based bricks, and passive cooling strategies in hot and humid climates. The study concludes that combining vernacular principles with tested alternative materials can deliver affordable, low-carbon, thermally comfortable housing, while also supporting local livelihoods. Limitations and directions for future empirical field monitoring and detailed life-cycle assessment are outlined.

Keywords: sustainable housing, compressed stabilised earth blocks (CSEB), bamboo structure, fly ash bricks, embodied energy, passive design, tropical climate

Introduction

1. INTRODUCTION

The building sector consumes roughly 30 - 40% of total energy use and is responsible for about one third of global CO_2 emissions. A large portion of this impact is embedded in materials such as Portland cement and fired clay bricks, whose production relies on high-temperature, fossil-fuel-intensive processes. At the same time, in tropical climates, conventional housing often provides poor thermal comfort, which then drives increased use of fans and air conditioning, further raising operational energy use and associated emissions.

For low- and middle-income households, this environmental problem intersects directly with affordability. Rising material prices, dependence on long supply chains, and energy intensive construction techniques have made home building increasingly expensive. In many contexts, households are effectively paying more to live in houses that are hotter and more uncomfortable than vernacular alternatives.

This paper responds to that tension by exploring a housing design that deliberately moves away from “high energy, low mass” construction toward a “low energy, high mass” approach, using locally appropriate materials and passive design strategies. The work is based on a design project titled *Sustainable Housing Design: A Comparative Study of Low-Cost, Local Materials vs Conventional Construction*, which develops a small tropical housing unit and evaluates it through embodied energy analysis and thermal performance simulation.

2. Literature review

Life-cycle assessment (LCA) studies consistently show that fired clay bricks are highly energy- and carbon-intensive. For example, Dabaieh et al. (2020) report that for every 1000 fired bricks, embodied energy reaches about 4250 MJ and embodied carbon about 5502 kg CO_2e, once raw material extraction, manufacturing, and delivery are included. VBN By contrast, sun-dried clay bricks in the same case study require only 0.033 MJ and emit about 0.24 kg CO_2e per 1000 bricks, yielding potential savings of 5305 MJ and 5907 kg CO_2e if substituted one for one.

Other studies focusing on kiln-fired bricks in South Asia and elsewhere report similarly high carbon footprints linked to fuel use, process emissions from calcining clay, and long transport distances. These findings highlight the importance of shifting away from fired bricks wherever feasible, particularly in rapidly urbanising regions.

Compressed stabilised earth blocks are formed by compacting a moist soil sand cement mix in a mechanical press, followed by curing rather than firing. They preserve many advantages of traditional adobe (local sourcing, low embodied energy, good thermal mass) while delivering improved strength, dimensional stability, and durability. Riza et al. (2011) demonstrated that CSEBs provide sufficient compressive strength and durability to replace conventional fired bricks for load-bearing walls when mix design and compaction are properly controlled. More recent experimental work on compressed earth blocks has characterized dynamic hygrothermal behaviour, confirming that such walls can buffer temperature and humidity swings in tropical humid climates. A 2020 study by Mbuh et al. emphasised that CSEB can simultaneously improve affordability and reduce environmental impact, provided that soils are correctly selected and stabilisation levels are appropriate to local exposure conditions.

Bamboo naturally combines high tensile strength, low density, and rapid renewability, making it a promising structural alternative to steel or reinforced concrete in small-scale buildings. Bredenoord (2024) synthesizes practical experience with engineered bamboo in low-cost housing, highlighting that laminated and treated bamboo members can reach structural performance comparable to timber, with a fraction of the embodied carbon of conventional materials. Beyond environmental metrics, bamboo offers aesthetic and psychological advantages: exposed bamboo roofs and frames create a sense of warmth and spaciousness that can help residents positively perceive “alternative” housing.

Fly ash, a by-product of coal combustion, is increasingly used as a binder or aggregate in bricks and blocks. Multiple LCAs have shown that fly-ash-based bricks, especially when combined with other industrial or agro-wastes, can dramatically reduce embodied energy compared with burnt clay bricks. A recent study in *Scientific Reports* by Singh et al. (2024) evaluated bricks made from fly ash, agro-forestry residues, and construction and demolition waste. They found that these bricks are 10–15 times less energy-intensive than burnt clay bricks, with total CO_2 emissions around 14.7 g CO_2/kg compared with roughly 97 g CO_2/kg for conventional bricks. Thermal parameters (U-value 0.5–1.2 W/m²K; thermal conductivity 0.4–0.5 W/mK) indicated superior insulation performance.

Passive cooling strategies orientation, shading, cross-ventilation, thermal mass and selective use of high-albedo surfaces are central to reducing cooling loads in tropical buildings. A recent systematic review of passive cooling methods for hot and humid climates covering nearly 40,000 publications concluded that natural ventilation and appropriate building envelope treatments remain the most robust and widely applicable techniques.

Similarly, work on energy efficient building design in tropical climates stresses:

1. Orienting buildings to minimize direct solar gain;
2. Providing cross-ventilation paths;
3. Shielding roofs and walls through overhangs and buffer spaces;
4. Using mass and insulation strategically to damp heat flows.

The design approach presented in this paper consciously builds on these established principles.

3. Methodology

This study adopts a comparative design and simulation methodology to evaluate the performance of two housing models that maintain similar floor areas, room configurations, and occupancy patterns. Case A serves as the conventional baseline, representing typical mainstream urban housing in tropical regions constructed with an RCC frame, fired clay brick infill, and cement plaster finishes. In contrast, Case B is the proposed sustainable unit, featuring locally produced load-bearing CSEB walls, a bamboo structural system for the roof and selected framing, internal partitions made of fly ash bricks, and exposed finishes that eliminate the need for plaster and paint. Designed specifically for a warm, humid tropical climate, the sustainable prototype integrates distinct passive strategies, including a north–south orientation to minimize solar exposure on longer façades and the placement of service spaces on the west to act as thermal buffers. Natural ventilation is minimized through large opposing openings for cross-ventilation and high-level ventilators that promote a stack effect to exhaust hot air. Additionally, extended roof overhangs reduce solar heat gain, while thick CSEB walls provide thermal mass to stabilize indoor temperatures by absorbing heat during the day and releasing it at night, ultimately aiming to reduce peak indoor temperatures and cooling energy needs.

Figure 1: - Front Elevation – Conventional Baseline (Case A)

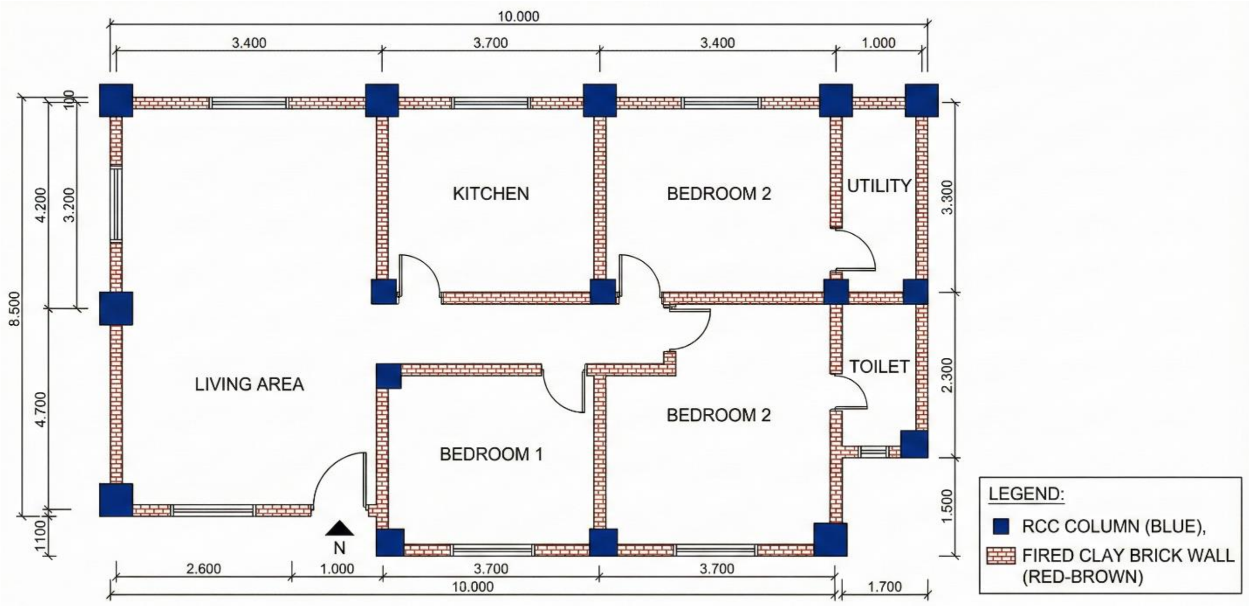


Figure 2: - Floor Plan - Conventional Baseline (Case A)

Within the study's comparative design-and-simulation methodology, Case A is established as the "conventional baseline". This model is intended to represent typical mainstream urban housing found in tropical regions. The construction specifications for Case A define it as a structure built with a Reinforced Cement Concrete (RCC) frame, utilizing fired clay bricks for infill walls. Unlike the proposed sustainable unit, the finishes in this conventional baseline consist of standard cement plaster. To ensure a direct and valid comparison, Case A is designed with the same floor area, specific room configuration (encompassing living area, bedrooms, kitchen, toilet, and utility), and occupancy pattern as the proposed sustainable unit (Case B).

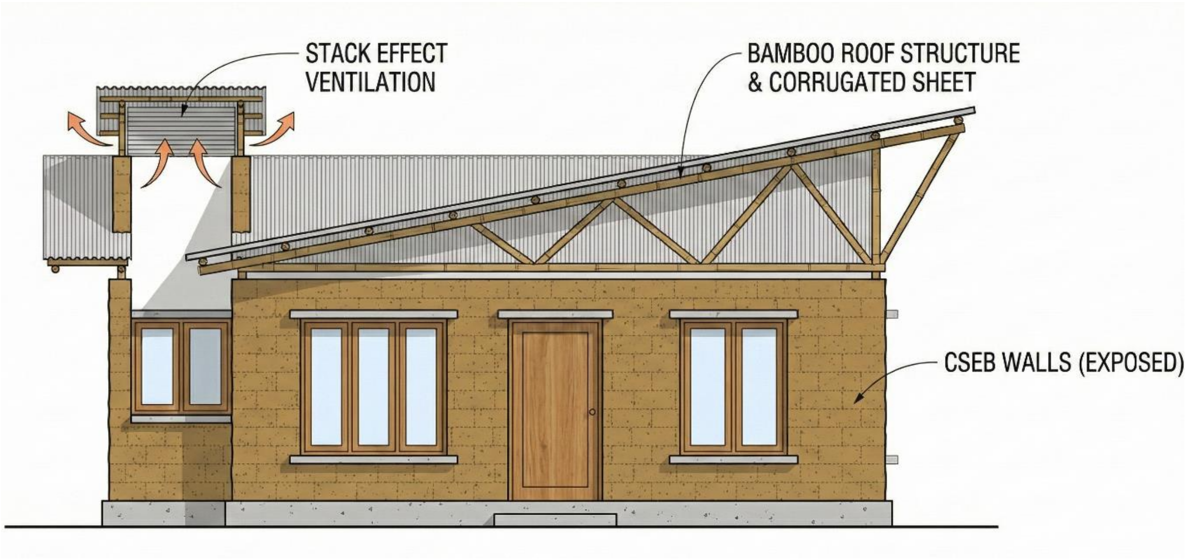


Figure 3:- Front Elevation – Sustainable Housing Unit (Case B)

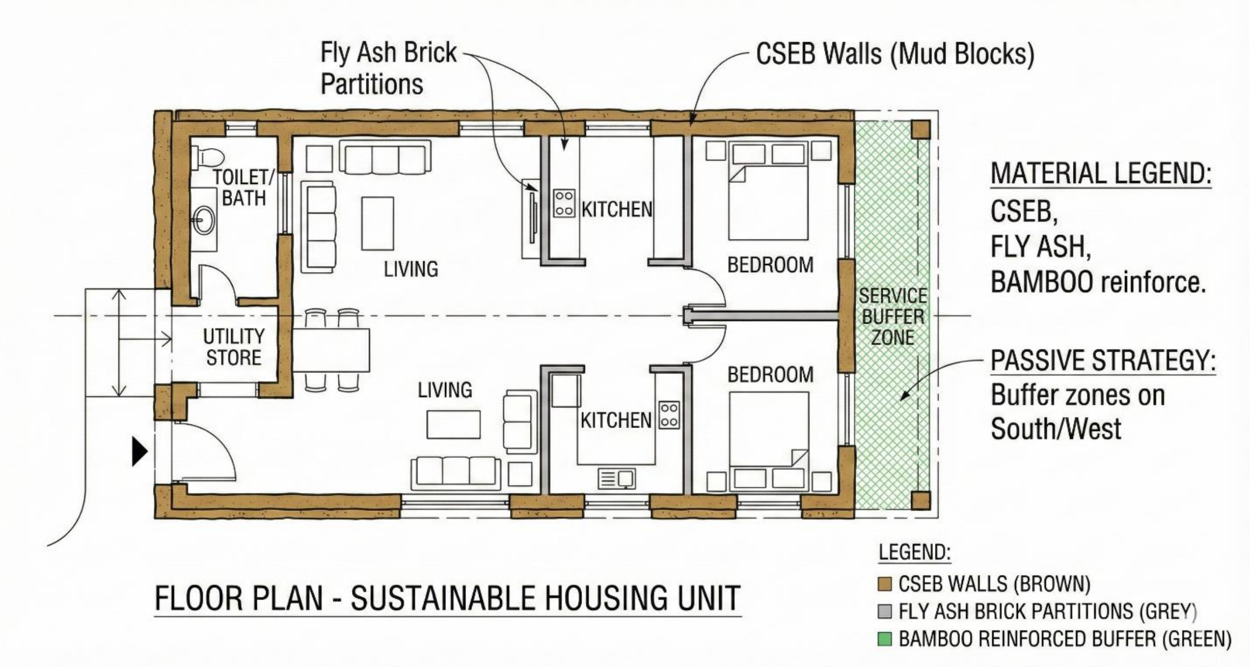


Figure 4:- Floor Plan - Sustainable Housing unit (Case B)

Based on the research design provided, Case B represents the proposed sustainable unit, which is designed specifically for a warm, humid tropical climate and maintains a similar floor area, room configuration, and occupancy pattern to the conventional baseline. This unit is constructed using locally produced load-bearing Compressed Stabilized Earth Blocks (CSEB) for walls, fly ash bricks for internal partitions, and a bamboo structural system for the roof and selected framing. Notably, the finishes are simplified, featuring exposed CSEB and bamboo surfaces without plaster or paint. Both cases assume similar floor area, room configuration (living room, bedrooms, kitchen, toilet, and utility spaces), and typical family occupancy. The primary building axis is aligned approximately north south, so that the longer façades face north and south. This reduces exposure to low-angle morning and afternoon sun on the east and west walls. Service spaces such as toilets, store, and utility are placed on the west side to act as buffer spaces, shielding the main living areas from evening heat. Large, opposing openings in the living and sleeping spaces enable effective cross-ventilation, harnessing prevailing breezes. High-level ventilators near the roof ridge and above internal doors allow hot air to escape, promoting a stack effect that draws cooler air in from lower openings. This combination is intended to maintain air movement without mechanical systems. Long roof overhangs and shaded verandas protect openings and walls from direct sun. The thick CSEB walls provide thermal mass, absorbing heat during the day and releasing it at night. This moderates indoor temperature variations and reduces peak heat levels.

Table 1: - Comparative material palette for baseline versus proposed unit

Component	Baseline (Case A)	Proposed (Case B)	Environmental notes
Structural frame	Reinforced cement concrete (RCC)	Bamboo primary structure (trusses, beams, selected frames)	Bamboo is rapidly renewable and low-carbon compared to RCC.
External walls	Fired clay brick with cement plaster	CSEB load-bearing walls, exposed finish	CSEB avoids kiln firing; lower embodied energy and CO_2 emissions.
Internal partitions	Fired clay brick	Fly ash bricks	Fly ash bricks utilize industrial waste with lower embodied energy.
Roof	RCC slab with waterproofing and tiles	Lightweight bamboo structure with insulated roof sheeting	Reduced weight, lower embodied energy, easier local assembly.
Finishes	Cement plaster and paint	Exposed earth blocks and bamboo surfaces	Eliminates additional materials and labour, reducing impacts and cost.

4. Performance assessment

This performance assessment methodology evaluates the proposed sustainable unit against a conventional baseline across three key domains. Embodied energy and carbon are estimated using element-level material quantities and published literature factors, indicating an approximate 70% reduction in embodied carbon. Thermal performance is assessed through dynamic simulations for a peak summer day (40°C outdoor maximum), showing indoor temperatures maintained up to 9°C cooler than outdoors due to high thermal mass, shading, and ventilation strategies. Finally, a simple first-cost comparison of material and labor differences reveals an approximate 22% lower construction cost, driven by reduced cement and steel use, local CSEB production, fly ash bricks, and exposed finishes.

Table 2: - Comparative of three-performance domain

Performance Domain	Assessment Methodology	Key Findings and Benchmark Indicators
Embodied Energy and Carbon (Cradle-to-Gate)	Material quantities are estimated at the element level (walls, roof, structure, finishes), utilizing embodied energy and CO_2 factors drawn from literature on fired bricks, earthen blocks, bamboo, and fly-ash-based products.	An overall 70% reduction in carbon footprint is adopted as the central indicator for the sustainable unit relative to conventional concrete construction.

Thermal Performance	Dynamic thermal simulations are conducted for a representative peak summer day with an outdoor maximum of 40 °C to compare indoor air temperatures in key rooms across both cases.	The benchmark performance is the proposed unit's ability to maintain peak indoor temperatures approximately 9 °C lower than the outdoor maximum.
Cost Analysis	A simple first-cost comparison is used, focusing on the differences in material and labour costs between the two cases.	The indicator is an overall 22% cost savings for the sustainable unit, driven by reduced material intensity, on-site CSEB production, and the omission of finishes like plaster and paint.

5. Results

The analysis suggests that replacing RCC and fired bricks with CSEB walls, bamboo structure, and fly ash bricks leads to an overall embodied carbon reduction of approximately 70% for the entire building. This is consistent with literature that compares fired bricks to alternative masonry units.

Table 3: - Examples of embodied energy and CO_2 for selected masonry units

Material / study	**Functional unit**	**Embodied energy (MJ)**	**Embodied CO_2 (kg CO_2e)**	**Notes**
Fired clay bricks (Dabaieh et al., 2020)	1,000 bricks	4,250	5,502	Conventional kiln-fired bricks.
Sun-dried bricks (Dabaieh et al., 2020)	1,000 bricks	0.033	0.24	Manual casting and sun drying; very low energy demand.
Burnt clay bricks (Singh et al., 2024)	1 kg of brick	~6.9 (per brick ≈ 2.3 kg)	~97	Typical burnt clay bricks.
Fly ash bricks (Singh et al., 2024)	1 kg of brick	~0.46 (per brick ≈ 3 k)	~14.7	Fly ash, agro-forestry residues, and C&D waste.
CSEB (various studies)	1 m² of wall	30–50 (range)	Lower than fired bricks	Values depend on soil and stabilization level.

These figures illustrate why shifting from fired bricks to CSEB and fly ash bricks can yield large reductions in embodied impacts at the building level.

The thermal simulation results for the proposed unit show significantly lower indoor temperatures than outdoors during a peak summer day. For a simple illustration, Table 3 presents a reconstructed hourly profile that aligns with the reported 9 °C maximum difference between indoor and outdoor temperatures.

Table 4: - Example hourly temperature profile for proposed unit vs outdoors (peak summer day)

Time of day	**Outdoor air temperature (°C)**	**Indoor temperature – proposed CSEB unit (°C)**
06:00	28	27
09:00	33	29
12:00	38	31

15:00	40	31
18:00	37	30
21:00	32	28

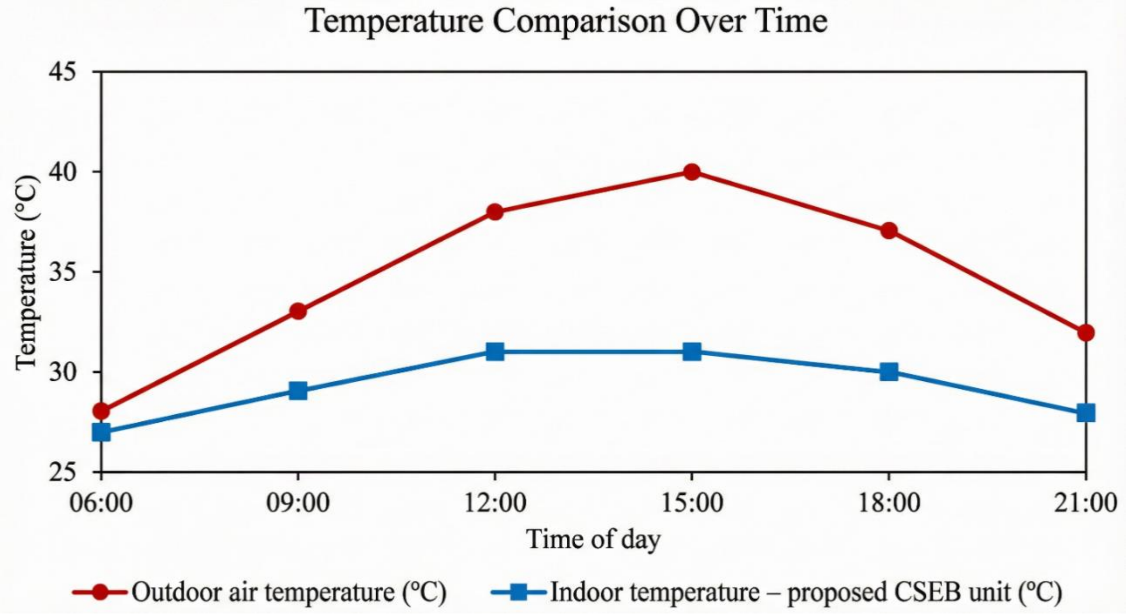


Figure 5: - Line chart Indoor vs outdoor temperatures on a peak summer day

The outdoor curve will show a steep rise to 40 °C in mid-afternoon, whereas the indoor curve peaks at around 31 °C and remains significantly lower throughout the hottest hours. Although equivalent data for the conventional baseline are not detailed here, studies of unshaded, poorly ventilated masonry buildings in tropical climates indicate that indoor temperatures in such structures often approach or even exceed outdoor peaks during the afternoon.

The comparative cost analysis reveals that the construction of the proposed sustainable unit is approximately 22% more economical than a conventional RCC-framed structure with fired brick infill. This reduction is primarily attributed to three synergistic factors. First, the design achieves lower material intensity by substituting fired bricks with Compressed Stabilized Earth Blocks (CSEB) and fly ash bricks, while simultaneously reducing cement and steel consumption through lighter, load-bearing masonry. Second, the adoption of simplified finishes—specifically exposed CSEB and bamboo surfaces—eliminates the need for cement plaster, putty, and paint, resulting in substantial savings in both materials and application time. Finally, the reliance on on-site CSEB production and local workforce significantly mitigates transportation and specialized labor costs, with the added benefit of generating local employment.

Table 5:- Qualitative cost comparison between baseline and proposed unit

Cost component	**Baseline (RCC + fired bricks)**	**Proposed (CSEB + bamboo + fly ash)**	**Relative cost impact**
Structural frame	High (cement, steel, skilled labour)	Moderate (bamboo + local connections)	Lower
Walling	Moderate/high (fired bricks + plaster)	Moderate (CSEB + simple mortar)	Lower

Roof	High (RCC slab, waterproofing)	Moderate (lightweight bamboo + sheeting)	Lower
Finishes	High (plaster, paint, putty)	Very low (exposed CSEB and bamboo)	Much lower
Total	100% (reference)	≈78% of baseline	≈22% saving in total construction cost

Beyond measurable performance metrics, the prototype is designed to deliver an uplifting living environment through specific architectural and experiential qualities. The interior features exposed earth walls that provide a tactile, natural surface often perceived as calming, while the bamboo roof serves a dual purpose as both a structural system and a distinct visual feature that adds spatial richness. These aesthetic elements are complemented by passive design strategies specifically generous daylighting and cross-ventilation, which enhance daily comfort and reduce reliance on artificial lighting and mechanical cooling. Collectively, these human-centred qualities are critical for fostering social acceptance and ensuring long-term satisfaction with alternative housing solutions.

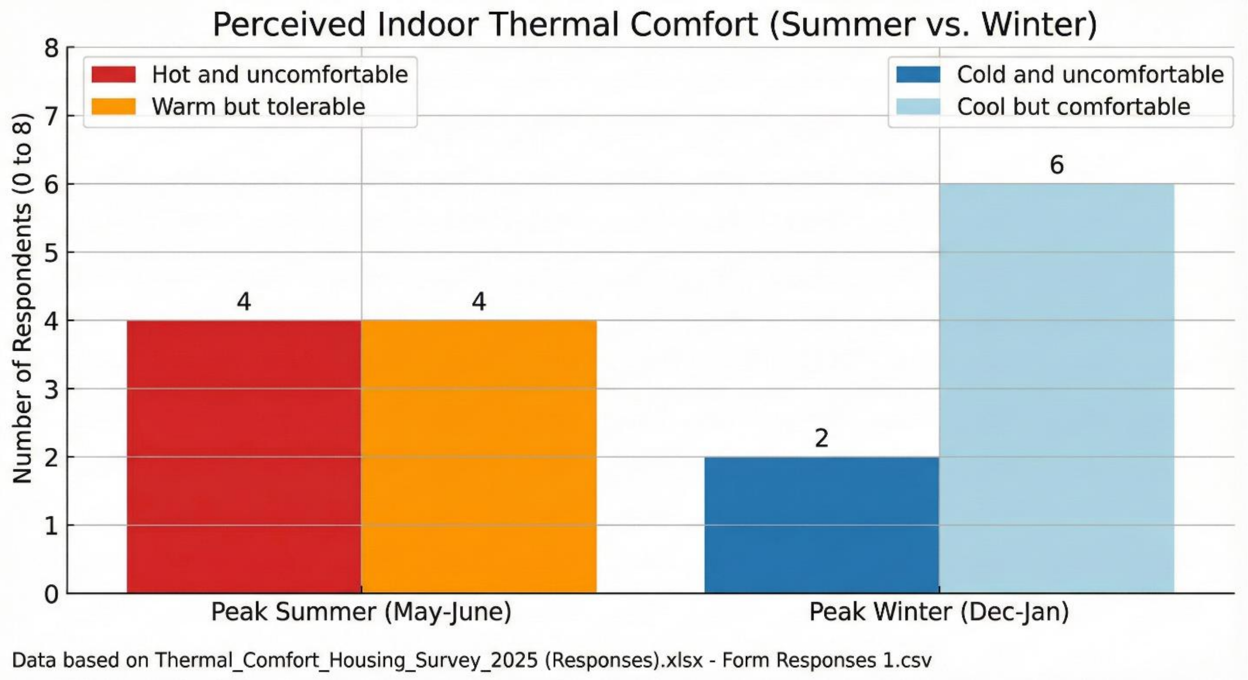
6. Discussion

The project's reported 70% reduction in embodied carbon is consistent in both direction and magnitude with existing LCA literature advocating for the replacement of fired bricks and cement-heavy structures with alternative materials. Research demonstrates that using sun-dried bricks or agro-forestry waste-based fly ash bricks instead of conventional fired bricks can significantly lower embodied energy and result in CO_2 intensities 4–8 times lower. Similarly, the thermal performance results, indicating peak indoor temperatures approximately 9 °C below outdoor maxima, align with broader studies on passive cooling in hot and humid climates, which repeatedly identify strategies such as orientation, cross-ventilation, shading, and the selective use of thermal mass as robust methods for lowering indoor temperatures. Experimental studies further confirm that the dynamic hydrothermal behaviour of CSEB walls can substantially improve indoor comfort in tropical climates.

The combination of lower upfront costs, reduced embodied carbon, and improved thermal comfort presents compelling implications for affordable housing policy and practice. These factors directly translate into improved affordability and health for households, enable governments to support climate goals without increasing social housing budgets, and generate skilled and semi-skilled local employment through on-site material production. However, real-world adoption relies heavily on the establishment of supportive building codes, clear structural design guidelines for bamboo and earth construction, and comprehensive training programmes for artisans. Furthermore, mainstreaming these materials requires overcoming persistent perceptions that equate earth and bamboo with poverty or temporary shelter; successful demonstrator projects displaying strong aesthetic and performance qualities are essential to shift this narrative.

Significant technical challenges and research limitations must also be acknowledged. The durability of CSEB is highly dependent on soil selection, stabilizer content, and curing, with poor practice leading to erosion or cracking, while bamboo requires careful seasoning, treatment against moisture and insects, and appropriate connection detailing. Additionally, current building standards often lack adequate provisions for these alternative materials, necessitating urgent updates. Finally, this study is limited by its reliance on a single prototype design and performance simulations rather than long-term monitoring. Future research should necessitate full process-based LCAs, direct field measurements to strengthen thermal evidence, and context-specific analyses to account for variable local costs and supply chains.

The pilot survey reveals that residents struggle significantly with summer thermal discomfort, leading to a high reliance on energy-intensive cooling systems. Despite low initial awareness of sustainable building alternatives, there is a strong willingness to adopt them, driven by a universal motivation for energy cost savings and high environmental concern. The primary barrier facing these alternative materials is not a lack of interest, but rather user anxieties regarding their long-term durability and maintenance.



Data based on Thermal_Comfort_Housing_Survey_2025 (Responses).xlsx - Form Responses 1.csv

Figure 6:- Thermal Comfort Perception summer vs. winter

7. Conclusion and future research

This paper presented a comparative study of a tropical housing prototype that substitutes conventional RCC and fired brick construction with a low-energy, high-mass material palette consisting of CSEB walls, a bamboo structure, and fly ash bricks, combined with robust passive design strategies. The results demonstrate that this integrated approach yields significant multi-dimensional benefits, most notably: a reduction in embodied carbon of approximately 70% relative to the RCC–fired brick baseline, primarily driven by material substitution and reduced finishes; a lowering of construction costs by roughly 22%, attributed to the use of local materials, on-site production, and the elimination of plaster and paint; and substantially improved thermal performance, where peak indoor temperatures on a 40 °C summer day remain approximately 9 °C cooler than the exterior due to optimized orientation, shading, ventilation, and thermal mass. Taken together, these outcomes substantiate the claim that sustainability in housing need not be treated as a luxury add-on, but rather constitutes a viable pathway toward delivering more affordable, comfortable, and dignified homes.

To realize the full potential of these alternative solutions in practice, it is imperative to integrate CSEB, bamboo, and fly ash bricks into local building standards, supplemented by clear technical guidance and comprehensive training programs for masons, carpenters, and engineers. Furthermore, utilizing pilot projects as live laboratories is crucial for refining construction details and building public trust. Building upon this foundational study, future research should conduct detailed process-based LCAs of completed houses, including use-phase energy analysis, alongside long-term field monitoring of indoor climate, user comfort, and maintenance needs. Subsequent investigations should also explore prototype variations adapted to different plot sizes, social contexts, and climate sub-zones, while simultaneously examining the social acceptance, gendered use of space, and cultural meaning attached to earth and bamboo architecture within diverse communities.

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