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Citation for the original published paper (version of record):

Guo, X., Dai, S., Yan, J. et al (2025). Comparative Life Cycle Assessment and Cost Analysis of Brick-and-Concrete and Modern Rammed
Earth Houses: A Case Study in Rural China. SUSTAINABLE BUILT ENVIRONMENT CONFERENCE 2025, 1554. http://dx.doi.org/10.1088/1755-1315/1554/1/012086

IOP Conference Series: Earth and Environmental Science

PAPER • **OPEN ACCESS**

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To cite this article: X Guo *et al* 2025 *IOP Conf. Ser.: Earth Environ. Sci.* **1554** 012086

IOP Conf. Series: Earth and Environmental Science **1554** (2025) 012086 doi:10.1088/1755-1315/1554/1/012086

Comparative Life Cycle Assessment and Cost Analysis of Brick-and-Concrete and Modern Rammed Earth Houses: A Case Study in Rural China

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Abstract. In addressing global climate change, China's rural housing renewal offers a critical opportunity to enhance sustainability. While brick-concrete structures dominate rural areas, modern rammed-earth houses are emerging as a promising alternative due to their environmental and economic advantages. However, there is a lack of quantitative comparisons between the life cycle performance of these housing types, creating a gap in evidence-based guidance for sustainable rural construction. This study examines two representative houses in Ningyuan County, Hunan Province: one rammed-earth and one brick-concrete. By analyzing their design, construction processes, expenditure patterns, and labor/material requirements, the research employs Life Cycle Assessment (LCA) to quantify carbon emissions and Life Cycle Costing (LCC) to assess financial expenditures. The study identifies discrepancies between pre-construction estimates and post-construction measurements of the rammed-earth house's lifecycle performance, investigating causes to inform future practices. Through comparative analysis of environmental and economic factors, such as material reuse, building performance, local sourcing, and social sustainability, the research highlights the strengths and weaknesses of both housing types. These findings provide empirical evidence to support the broader adoption of rammed earth. It also establishes preliminary localized datapoints of embodied carbon (241 kg CO_2e/m^2 for rammed earth, 417 kg CO_2e/m^2 for brick-concrete) for rural housing in southern China. Grounded in a case study from a rural, underdeveloped village, the results offer insights for construction practices in similar contexts in the Global South.

1. Introduction

The global construction sector is responsible for nearly 40% of annual carbon emissions [1], with rural housing in lower-income countries representing a significant but often overlooked component. While Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) methodologies are commonly applied to urban buildings [2], their use in rural contexts—especially in vernacular architectures like rammed earth—remains underexplored. This gap limits the development of evidence-based guidelines for sustainable rural construction, despite its critical socioeconomic and environmental importance in the Global South.

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1.1. Existing Research and Limitations

In South Asia, about 72% of the population lives in rural areas [3], and in West and Central Africa, the figure is 70% [4]. In China, rural buildings account for over 90% of the total structures, making rural construction crucial to achieving the Sustainable Development Goals (SDGs) and tackling global climate challenges [5].

While lifecycle performance has gained academic attention, most studies focus on material-level carbon emissions or urban buildings constructed with industrialized materials. Consequently, real-world case studies comparing rural construction, especially modern rammed-earth houses, are scarce. Some research has quantified the carbon benefits of standardized rammed earth [6], evaluated thermal performance in modern rammed earth houses [7], and compared rammed earth to traditional masonry walls [8], but studies on the application of modern rammed earth in rural, lower-income regions remain limited.

Rural rammed earth construction practices differ markedly from urban settings, making it difficult to directly apply urban findings to rural areas. Material availability, transportation constraints, construction organization, and local acceptance of new technologies differ greatly between rural and urban environments [9,10]. Furthermore, rural communities often face labor shortages due to depopulation and an aging population, while lower income levels increase sensitivity to construction costs. Local knowledge, cultural traditions, and living habits also significantly affect the lifecycle performance of buildings [11].

Moreover, the post-construction performance of rural rammed earth projects remains largely undocumented. There are few empirical studies that include actual material and energy consumption measurements in rural houses [12], leading to lifecycle assessments that are based on design-stage assumptions, rather than local realities. As a result, although rammed earth is widely used in rural areas, contemporary sustainability assessments lack sufficient data to verify its viability as a scalable alternative to brick-concrete houses.

1.2. Significance of Addressing Research Gaps

Addressing these gaps is crucial. Rural construction is accelerating due to China's urbanization challenges and ongoing rural revitalization policies. As the government invests heavily in rural infrastructure, the demolition, renewal, and construction of rural houses are taking place at a large scale. Without localized sustainability guidelines, these efforts may hinder China's carbon-neutral goals and cause irreversible damage to rural development.

Furthermore, sustainability assessments need to be tailored to rural contexts. Urban-based design tools often overlook the unique characteristics of rural areas. For example, while labour-intensive rammed earth construction may incur higher initial costs, it offers long-term environmental benefits, supports local economies, and preserves cultural landscapes. These factors, which are frequently overlooked, are critical in rural settings. Real-world quantitative studies can help establish more appropriate sustainability benchmarks for these areas.

This research also holds global relevance. Countries in the Global South, like India and Ethiopia, which have a tradition of earth construction, face similar challenges in balancing modernization with sustainability. The findings from this study, particularly the localized LCA data, could provide valuable guidance for policymakers seeking adaptive solutions over carbon-intensive alternatives.

1.3. Research Objectives

This study investigates the lifecycle environmental and economic performance of modern rural rammed earth houses in comparison with conventional brick-concrete houses, situating both

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within their socio-technical contexts over a 50-year lifespan. To ensure empirical rigor, design-stage LCA and LCC projections are integrated with post-construction measurements, allowing us to identify and analyze discrepancies between predicted and actual carbon emissions and costs for the rammed earth dwelling. In addition, the study examines how variables such as local material sourcing, labor inputs, and building thermal performance collectively shape each house's sustainability profile. Finally, these insights are synthesized into practical recommendations that balance technical feasibility with socioeconomic and cultural considerations, thereby guiding the low-carbon transformation of rural construction in lower-income regions.

2. Methods

2.1. Data Source and Fieldwork

This study focuses on empirical data to capture the socio-technical complexities of rural housing in China. Data collection was conducted through three primary channels:

1. Design and Construction Documents: These were obtained from Donggua Chong Village in Ningyuan County, Hunan Province (Figure 1). This village has a rich history of earthen housing, though many traditional houses have been replaced by brick-concrete structures as part of ongoing rural renewal efforts. Since 2021, the Chan Cheung Mun Chung Charitable Fund (CCMCCF) has supported the gradual introduction of modern rammed earth technology through renovation, retrofitting, and new construction projects. From CCMCCF's database, we acquired original design blueprints, design-stage LCA/LCC estimates, material procurement records, and labor logs for a new modern rammed earth housing project. We then performed statistical analyses on Material procurement (calculating average quantities, cost variances, and distribution across key material categories), Labor logs and Design vs. actual performance. These analyses provided detailed insights into resource use patterns and informed the calibration of our lifecycle assessments.

2. Post-Occupancy Monitoring: To assess the operational performance and carbon emissions of the modern rammed earth house, we installed calibrated sensors inside the house and in the surrounding village environment. These sensors continuously recorded key climatic parameters (temperature, humidity) for comparative analysis. In addition, data on villagers' fuel usage, common electrical appliances, and electricity bills were collected, supplemented by interviews with residents to quantify the impact of rural living on energy consumption.

Figure 1. Masterplan of Donggua Chong Village.

3. Comparative Case Study: A brick-concrete house was selected as a control for comparison. Field measurements, billing data, and structured interviews with homeowners and local craftsmen provided essential information on material usage, labor hours, and maintenance costs, establishing a baseline for comparison. The validity of these calculations was further confirmed by cross-referencing relevant literature.[13]

2.2. Analysis Framework

To systematically quantify the environmental and economic impacts of the construction projects, this study employs Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) methodologies. According to EN15978, the building life cycle includes the production, construction, use, and disposal phases (Figure 2).

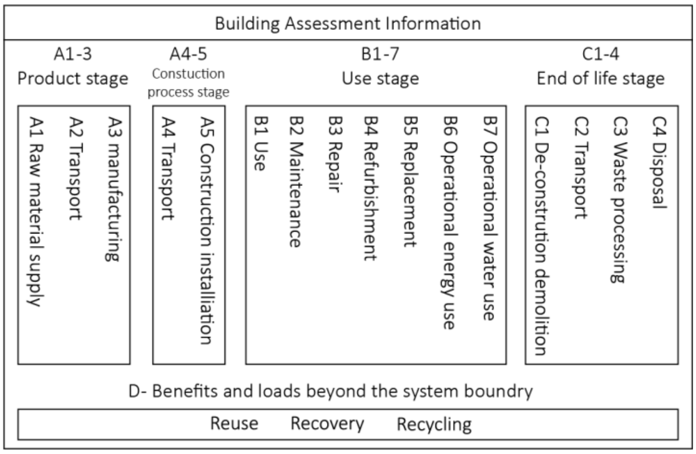

Figure 2. Building's life cycle stages according to EN 15978.

LCA is conducted in accordance with ISO 14040, which involves four steps: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation. The goal of this study is to compare the carbon footprint and economic costs of two rural housing types, each with a lifespan of 50 years. The study uses Global Warming Potential (GWP) as the primary environmental impact assessment indicator, with system boundaries defined from cradle to grave (A1-C4). During the use phase, categories B1-B5 are treated as a single module, while B6 is calculated differently before and after construction. Energy consumption is simulated during the design phase, with actual electricity consumption data used post-construction. The B7 module is excluded, as the village's water supply is not municipally sourced.

The life cycle inventory (LCI) data for modules A1–A3, B4, and C3–C4 were drawn from Ecoinvent v3.x and Environmental Product Declarations (EPDs) compliant with ISO 14044 and EN15804, then regionally adapted in One Click LCA to reflect local conditions. Specifically, the Chinese electricity grid mix (with Hunan province proportions) replaced the default European profile; where Chinese EPDs were available—for example, for cement and steel production—these were used directly, and remaining global datasets were adjusted using regional emission factors. Transport data for modules A4 and C2 were derived from village-to-market distances collected in interviews. Modules A5 and C1, which contribute minimally to total impacts, relied on empirical formulas from local building codes and original project documents. This approach ensures that our LCI reflects both international standards and the specific technological and logistical context of rural Hunan.

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The study integrates technical assessments with design guidance by analysing results across three dimensions: technical performance, socio-economic feasibility, and cultural-environmental synergy. In the case of the rammed earth house, its estimated environmental and economic performance during the design phase is systematically compared with post-completion measurements to identify the sources of discrepancy. The life cycle carbon emissions and costs of both housing types are further analysed in terms of materials, labour, and maintenance. Semi-structured interviews with residents explore how performance differences influence their housing choices and how sustainable construction practices can be integrated with the local community's cultural context.

3. Results and discussion

3.1. Case Study: The Rammed Earth House

The modern rammed earth house (Figure 3) is a two-unit duplex with a total floor area of 300 m^2. Its load-bearing walls are constructed from locally sourced rammed earth stabilized with 7% Portland cement by volume. The roof employs a steel system—comprising approximately 5 t of structural steel—to support traditional chinese tiles, enhancing seismic performance and providing a moisture barrier. Window frames are aluminum, and the building footprint is oriented to maximize passive solar gains while enabling cross-ventilation. During the hot summer months, the indoor temperature of the rammed earth house is about 5°C lower than the outdoor temperature (Figure 4), significantly improving indoor comfort.

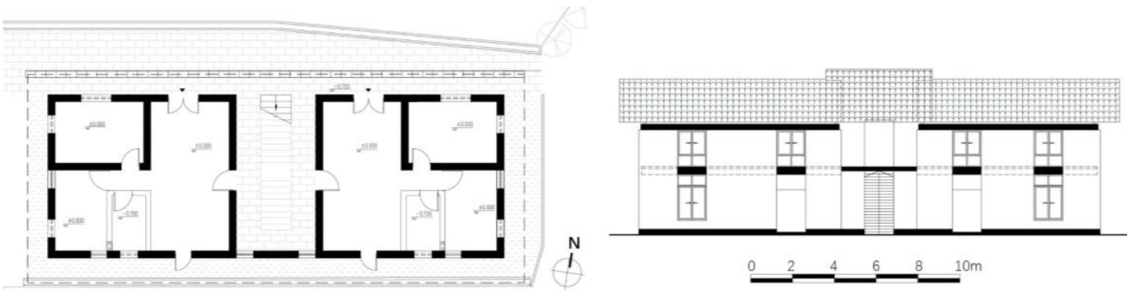

Figure 3. Site plan and north façade of the modern rammed earth house.

The lifecycle carbon emissions calculation reveals that the embodied carbon of the modern rammed earth house is 240.58 kg $CO^{2}e/m^{2}$. The major sources of carbon emissions are the building materials, the use phase, and the construction phase (Figure 5). The construction phase contributes significantly to emissions due to the use of a pneumatic tamper instead of manual rammed earth construction. While this method increased the compaction of the walls and shortened the construction period, it consumed more energy. From the materials used, concrete, steel, aluminum windows, and bricks were the primary sources of carbon emissions, accounting for 36.4% of the total emissions. The earth used for the rammed earth walls is locally sourced and produces almost no carbon emissions; however, the cement used as a stabilizer contributed to the carbon footprint to ensure the wall strength met local seismic requirements and to reduce construction difficulty.

During the design phase, the designer estimated the carbon emissions of the house, but after completion, it was found that the actual carbon emissions differed from the estimated values.

Firstly, tests revealed that the local soil had a lower cohesion than expected, requiring the addition of 7% cement by volume as a stabilizer, which contributed to 4% (approximately 5.1 tons) of the total lifecycle carbon emissions. Secondly, the modern rammed earth technology applied a new construction process and tools, and local craftsmen made mistakes and had to redo some work during the learning process. This led to material and energy waste, increasing carbon emissions and extending the construction period. Additionally, when simulating the energy consumption of the house during the use phase in the software, the electricity consumption of the rural household was overestimated, while the tolerance of residents to indoor temperatures was underestimated. As a result, the actual carbon emissions during the use phase were lower than expected. Finally, some building materials had to be transported a longer distance than anticipated, leading to increased carbon emissions. These factors should be considered in future construction practices.

3.2. Comparative Analysis: The Brick-Concrete House

The brick-concrete house (Figure 6) covers 170 m^2 and uses 180 mm thick clay brick walls integrated with a reinforced concrete frame. Its roof consists of a concrete slab reinforced with 0.5 t of steel rebar, finished with a thin cement-sand layer and ceramic tiles. With minimal insulation, this building exhibits higher thermal transmittance. During construction, the primary labor demands were for the tasks of formwork, masonry, and plastering, which are common in the region. While skilled workers for these tasks are readily available in nearby towns, their fees are relatively high.

The lifecycle carbon emissions calculation reveals that the embodied carbon of the brick-concrete house is 417.32 kg $CO^{2}e/m^2$, approximately 173% of the modern rammed earth house's

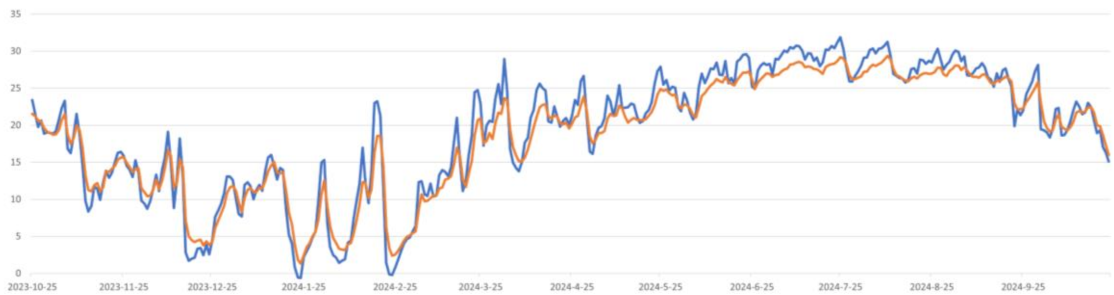

Figure 4. Comparison of average daily indoor (orange line, ℃) and outdoor (blue line, ℃) temperatures in the rammed earth house. No active heating or cooling equipment was used during the monitoring period, allowing the data to reflect the building's passive thermal regulation performance.

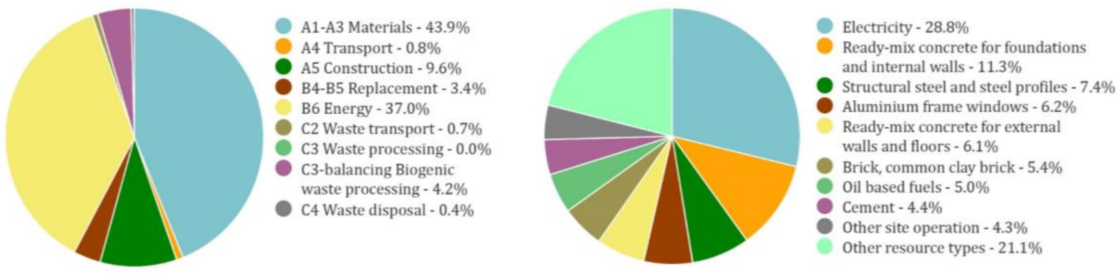

Figure 5. Life-cycle overview of the rammed earth house's total GWP, categorized by stages (left) and resource types (right).

Figure 6. Site plan and north & west façades of the brick-concrete house.

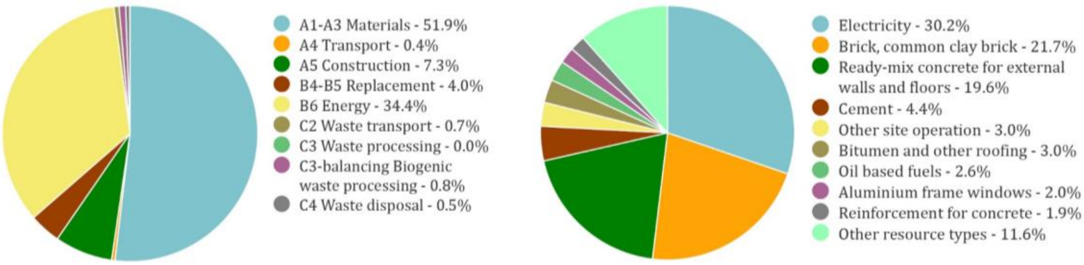

Figure 7. Life-cycle overview of the brick-concrete house's total GWP, categorized by stages (left) and resource types (right).

embodied carbon. The carbon emissions from building materials alone (A1-A3) account for 51.9% of the total carbon emissions, which amounts to 370.59 kg CO^2e/m^2 (Figure 7). This is significantly higher than the 214.49 kg CO^2e/m^2 for the modern rammed earth house. The carbon emissions per square meter during the use phase are also relatively higher (Table 1). In terms of materials, brick, concrete, and cement are the primary sources of carbon emissions, contributing to 45.7% of the total emissions. This demonstrates the substantial advantage of using rammed earth as an exterior wall material in reducing carbon emissions.

In the lifecycle cost analysis, we found that the cost difference between the two houses during the material and construction phases was relatively small. From a materials perspective, the rammed earth house benefits from locally sourced soil for the exterior walls, which reduces some material costs. However, mistakes made during the new technology implementation and the additional machinery required increased the costs. Moreover, the steel used in the roof structure of the modern rammed earth house was relatively expensive. On the other hand, the main materials used in the brick-concrete house are industrially produced, which keeps costs lower. From a labor perspective, although rammed earth construction requires ongoing technical guidance and has a longer construction period, much of the labor involved in the rammed earth process can be performed by lower-wage workers. Additionally, the aesthetic finish of rammed earth walls reduces the need for too much decoration, which results in a lower demand for skilled workers and saves on labor costs. However, from a full lifecycle cost perspective, the modern rammed earth house incurs lower costs during the use phase compared to the brick-concrete house. This is primarily due to the better thermal performance of the rammed earth house, which reduces cooling and heating demands, leading to lower energy costs. In the demolition phase, although the addition of stabilizers to the rammed earth affects the process of the material

Table 1. LCA & LCC calculation results for post-construction houses : average GWP (kg CO_2e/m^2) and cost (CNY/m^2) for rammed earth and brick-concrete houses, broken down by lifecycle stages.

Stages	Result category	Cost of rammed earth house CNY/m^2	Cost of brick - concrete house CNY/m^2	GWP of rammed earth house kg CO^2e/m^2	GWP of brick - concrete house kg CO^2e/m^2
A1-A3	Construction materials	726.24	715.79	214.49	370.59
A4	Transport to the building site	29.98	23.53	4.00	3.06
A5	Construction process	456.48	463.24	46.67	52.35
B1-B5	Use phase	346.88	416.62	16.33	28.82
B6	Energy consumption	81.67	132.35	176.67	247.06
C1	Deconstruction	15.00	40.00	0.40	0.71
C2	Waste transport	6.67	23.53	3.33	4.71
C3	Waste processing	1.70	1.70	0.06	0.03
C4	Waste disposal	-	-	1.97	3.76
-	Life cycle cost	1664.62	1816.76	-	-
-	Material and construction cost	1212.71	1202.56	-	-
-	Embodied carbon	-	-	240.58	417.32

[a] The calculation of embodied carbon in the table is the sum of the carbon emissions from stages A1-A4, B4-B5, and C1-C4 of the house. In this study, the use-phase modules B1–B5 were conceptually grouped for system boundary definition, but only B4 (replacement) and B5 (maintenance) were quantified due to data availability and relevance. Modules B1–B3 were excluded from calculations as they were either negligible or not applicable in the rural context.

[b] For the end-of-life phase (C1–C4), material treatment scenarios were based on regional construction practices. Rammed earth was assumed to be reused on-site with minimal processing. Bricks and concrete were considered landfilled after basic crushing. Steel components were assumed to be 85% recycled, while wood was modelled as incinerated without energy recovery. These assumptions were adapted from Ecoinvent datasets and adjusted based on local situation.

returning to the environment, the impact on demolition costs is minimal in rural areas. Furthermore, the higher steel content in the case of the rammed earth house means that steel recovery during demolition further reduces demolition costs.

3.3. Social and Cultural Perspective Analysis

From the perspective of social sustainability, the modern rammed earth house case study demonstrates that the labor-intensive nature of rammed earth construction provides low-barrier employment opportunities for the local population. Using locally sourced bio-based and recycled materials (such as bamboo, wood, and old tiles) not only reduces the environmental burden caused by industrial production and transportation, but also creates more opportunities for local craftsmen, strengthening the cohesion and resilience of rural communities. This approach helps foster a more sustainable, self-sufficient building culture. In discussions with local villagers, we learned that their long-standing tradition of using earth as a building material has led to a natural acceptance of rammed earth houses. Therefore, it can be expected that as more modern rammed earth houses are built, construction costs will be spread across multiple projects, and the clustering effect will lead to the architectural style being adopted in surrounding villages, preserving the community's traditional earthen building culture.

The research also suggests several key areas that should be addressed when applying modern rammed earth technology in underdeveloped rural regions. First, it is important to inform local communities about the benefits of using locally sourced materials in modern rammed earth houses, which can increase the acceptance of this new technology. Second, the design should take into account local climate, lifestyle, and functional needs, simplifying the design to reduce waste. Lastly, it is essential to train a skilled workforce of rammed earth builders locally, ensuring standardized construction processes, reducing rework and waste. This not only impacts carbon emissions and construction costs but also promotes knowledge-sharing within the community.

4. Conclusion and research limitations

This study demonstrates the advantages of modern rammed earth houses over brick-concrete alternatives, particularly in terms of the use of locally sourced materials. However, it also highlights some challenges, including the potential for construction errors, rework, and longer building periods during the early adoption of the technology. From a lifecycle perspective, promoting modern rammed earth houses can significantly reduce carbon emissions and economic costs in both the material production and operational phases, while also contributing to the broader social and economic sustainability of rural communities.

The case study reveals that the successful implementation of modern rammed earth houses in underdeveloped rural areas requires a shift in mindset. Achieving this shift involves adopting locally appropriate designs, providing effective training for craftsmen, and standardizing construction processes. These efforts are essential to ensuring that the new technology is embraced by local communities without incurring unforeseen costs.

However, this research is based on a single case study, which may not fully represent the diversity of rural housing across different regions of China. To enhance the generalizability of the findings, future studies should expand the scope to include a wider range of case studies. This will help refine the conclusions. Furthermore, while this study centres on Global Warming Potential, future research should consider a wider range of environmental indicators (such as ozone depletion potential) to provide a more holistic assessment of rural housing sustainability.

5. Acknowledgements

We sincerely thank the Chan Cheung Mun Chung Charitable Fund (CCMCCF) for the generous financial and logistical support, which made both the research and the on-site construction of the rammed earth houses possible. We are especially grateful to Professor Wenfeng Bai for his structural consulting and to Professor Jing Xiao for his guidance on architectural design—both from Kunming University of Science and Technology (KUNST).

Our heartfelt thanks go to Ms. Yong Dai, Ms. Emily Li, Mr. Ling Yang for their outstanding efforts in project management, data recording and on-site supervision. We are deeply indebted to the villagers of Donggua Chong Village in Ningyuan County for their warm collaboration and active participation in data collection, all of which provided this study with invaluable local knowledge and support.

We extend our sincere appreciation to the broader local community for their commitment to promoting rammed earth as a sustainable and culturally meaningful building practice.

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