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Sustainability-based comparison of local bahareque and conventional reinforced concrete structural system for social housing construction

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Introduction: The housing deficit necessitates government interventions, including social housing for vulnerable populations. This has led to diverse construction solutions that address homelessness while promoting local and traditional building methods. Beyond feasibility, sustainability is crucial.

Methods: This research evaluates the sustainability of two structural systems, bahareque and reinforced concrete, for low income housing in Ecuador using a multi-criteria decision-making model. Bahareque is a traditional construction system based on the use of Guadua cane, valued for its low environmental impact. The analysis was conducted through the Integrated Value Model for Sustainable Evaluation (MIVES), considering economic, environmental, and social factors. Indicators were defined through studies and expert surveys.

Results: The analysis included material and construction costs, resource consumption, emissions, and social impacts like working conditions. Traditional and indigenous materials were also assessed for sustainability potential. Results showed bahareque had a sustainability index (SI) 17.5% higher than reinforced concrete.

Discussion: This framework can be adapted to different contexts and preferences by modifying its components and criteria.

KEYWORDS

reinforced concrete, bahareque, MIVES, sustainability, sustainable cities

1 Introduction

With the global population nearing 8 billion, ensuring access to adequate housing constitutes a major challenge for governments worldwide, impacting low, medium and high income countries (UNFPA, 2023). Housing is recognized as a fundamental determinant of human health and well-being; its absence can lead to adverse consequences, including physical and mental health problems, increased disease susceptibility and hospitalization rates, substance abuse disorders, limited access to primary healthcare, and income instability (Ramage et al., 2021). In 2023, the UN reported that approximately 1.1 billion people live in inadequate housing, with nearly 2 billion residing in informal settlements (United Nations, 2023). These figures threaten the achievement of Sustainable Development Goal 11 "Sustainable Cities and Communities," which aims to ensure universal access to adequate, safe, and affordable housing and basic services, while simultaneously reducing the per capita environmental impact of cities, particularly concerning air quality and waste management (Naciones Unidas, 2023). In this context, the development of affordable housing is crucial for improving living conditions and fostering social equity.

While social housing represents a key solution for millions of homeless people, its development has historically prioritized lower upfront costs over quality and sustainability (Couret and Párraga, 2019). However, ensuring adequate living conditions implies considering factors such as energy efficiency and the quality of the indoor environment, aspects that directly influence the health and well-being of the occupants. In addition, the lack of sustainable-oriented measures in the design and construction of housing generates a greater environmental impact, since many buildings depend on mechanical air conditioning systems due to inadequate thermal regulation (Hernandez, 2018). In this sense, the development of housing solutions that, in addition to being economically accessible, promote the efficient use of resources and stimulate productive sectors linked to sustainable construction has been encouraged (Rodríguez-Díaz et al., 2023).

A key strategy in this context is the use of local materials, especially in less industrialized regions. The use of these resources not only leads to reduce the costs associated with the purchase and transportation of conventional materials such as steel and concrete, but also to strengthen the local economy and to reduce the environmental impact of the construction sector. In Latin America, the wealth of indigenous materials has allowed for significant architectural-tectonic innovations without compromising structural quality. For example, the use of stone and earth has been recurrent in housing projects (Ghisleni, 2024). In Argentina, the Sustainable Construction Manual establishes sustainability policies for state-financed housing, promoting the use of reused materials, technologies such as prefabricated systems, recycled products, certified wood and local materials (Ministerio de interior Obras Públicas y Vivienda, 2019). Similarly, a study by the Colombian Sustainable Construction Council reveals that 35% of residential projects in Colombia use low-emission materials. In addition, the materials used in various projects contain, on average, up to 8% recycled content, demonstrating that it is possible to develop sustainable alternatives adapted to the climatic and cultural conditions of each region (Pérez Godoy, 2022).

Studies evaluating sustainable construction practices across different regions have yielded compelling results. In Barcelona, a sustainability assessment using the MIVES multi-criteria model and the Knapsack algorithm for multi-material facades identified a concrete panel wall with rock wool insulation and plaster layers as achieving the highest sustainability index. This is due to the lower generation of waste, which improves its environmental performance, and the implementation of prefabricated systems, significantly reducing maintenance costs (Gilani et al., 2022). In Peru, an analysis of construction techniques highlighted reed-reinforced adobe (CRA) as the most advantageous option compared to other alternatives. This method proved to be cheaper and easier to build, making it easier for local communities to adopt (Cárdenas-Gómez et al., 2021). Research in Ecuador has demonstrated the sustainability and eco-friendliness of using recycled materials for structural elements due to their reduced carbon footprint and ease of transportation and assembly (Montero-Riofrio, 2024). Furthermore, the application of guadua cane in single-family homes in Ecuador has shown improved seismic performance and a 70% reduction in environmental impact from the structure (Tello-Ayala et al., 2023). These findings reinforce the need to explore construction methods that are structurally viable and allow minimizing environmental impact and promoting economic accessibility, as is the case with the bahareque.

In Latin America, housing construction has evolved with the adoption of industrialized systems that use thin reinforced concrete walls and reusable metal forms to reduce material and labor costs (Castillo et al., 2024). However, despite its strength and durability, concrete continues to be a material with a high environmental footprint, due to the extraction of raw materials, energy consumption in its production, and carbon emissions generated in its transportation. In contrast, alternatives such as bahareque have proven to be more sustainable and accessible by using local materials such as Guadua cane, reducing costs and minimizing environmental impact. Studies have explored the use of innovative materials such as oil palm fibers in reinforced concrete beams (Momoh et al., 2023), insulated hollow clay masonry or extruded polystyrene concrete walls (Mahlan et al., 2024), but these still present challenges in terms of economic viability and accessibility for low-income communities. Bahareque emerges as an alternative that is thought to meet the sustainability criteria and to adapt to the economic and social conditions of affordable housing. Nonetheless, no previous research has been carried out on the assessment of the sustainability performance of this technique for affordable housing.

The practical implications of using bahareque as a construction system are significant, especially in regions where local resources play a fundamental role in sustainable construction. Guadua cane, the main component of bahareque, stands out as an ecological, economical and earthquake-resistant material. However, its quality depends on an adequate process of cultivation, cutting, curing and storage (Llumiquinga, 2023). In addition, the sustainability and accessibility of bamboo in sustainable constructions in Latin America and Asia has been evaluated, offering low-cost and expandable housing within the urban context (Bredenoord, 2024).

Bamboo, a fast-growing and highly renewable plant, has gained recognition in construction due to its flexibility, compressive and tensile strength, and its ability to replace materials with a high carbon footprint, such as steel, bricks and concrete (Bredenoord, 2024). One of its most outstanding applications is the "bahareque" (or Quincha), a construction system that uses Guadua cane to form structural panels. This method, widely used in South America and Asia, is distinguished by its low cost, ease of construction and environmental sustainability, making it ideal for social housing projects. With proper maintenance, a bahareque house can last at least 30 years before requiring major repairs. In addition, its use of locally available materials reduces transportation costs and carbon emissions, while boosting local economies and employment (Mite-Anastacio et al., 2022). These characteristics position bahareque as a sustainable alternative to address the housing deficit in Ecuador, where the demand for affordable, durable and environmentally friendly housing continues to grow.

Previous research has analyzed the sustainability of bamboo, highlighting its high mechanical properties, low environmental impact, and rapid growth rate (Xu et al., 2022). On the other hand, several studies have shown the negative effects of concrete reinforcement, particularly in terms of high energy consumption and CO_2 emissions (Xi et al., 2023). It is important to note that the construction industry is responsible for approximately 50% of global greenhouse gas emissions, with concrete being the most widely used material and, therefore, the one that contributes the most to this percentage (Jang et al., 2015).

Despite this evidence, there are still few studies that comprehensively compare the two construction systems, considering aspects such as local resource availability, life-cycle energy efficiency, economic and social costs, and adaptability to local conditions. In this context, the novelty of this research lies in the comparative evaluation, based on sustainability criteria, of a vernacular construction system such as bahareque and the widely used reinforced concrete within the social housing sector.

Unlike previous studies focused on individual aspects like cost or construction time, this study employs the Integrated Value Model for the Assessment of Sustainability (MIVES), a methodology that allows for a comprehensive and objective analysis by integrating diverse economic, environmental, and social criteria enabling a more complete and detailed assessment of the sustainability of each structural system (Boix-Cots et al., 2022). Thus, this research aims to determine which of the two systems, bahareque or reinforced concrete, is the most suitable for implementation in social housing projects, evaluating factors such as cost, durability, environmental impact, and social acceptance. This approach allows bahareque to be positioned as a local and traditional alternative to the reinforced concrete paradigm, promoting sustainable housing solutions adapted to their socioeconomic and environmental context.

2 Materials and methods

This study compares the sustainability of structural systems using the Integrated Value Model for Sustainable Assessment (MIVES), a multi-criteria methodology that objectively evaluates alternatives based on economic, environmental, and social dimensions. This approach provides a comprehensive view that facilitates decision-making in the sustainable construction sector.

2.1 Description of MIVES

MIVES is a decision-making approach that distinguishes itself by incorporating multiple criteria to assess different alternatives within a problem employing a sustainability index (SI). This SI is derived from the weighted sum of the evaluations across the various considered criteria and indicators (Josa et al., 2020). This method encompasses five distinct phases (Figure 1).

The initial phase involves the delimitation of the decision-making scope, encompassing the establishment of boundaries for the target and the system under analysis. The subsequent phase involves the definition of the decision tree, which hierarchically organizes the criteria and indicators subject to evaluation. This hierarchical structure commences with the sustainability pillars (economic, environmental, social) at the first level, followed by the criteria and finally, the specific indicators at the next level. In the third phase, value-generating functions are used to normalize the indicator variables, since these may have different units. These functions transform the data into a standardized range (from 0 for maximum satisfaction to 1 for minimum satisfaction) through the application of functions with diverse shapes, such as linear, concave, convex or S-shaped. The value functions are obtained by applying equations (1) and (2) as detailed in Supplementary material. The fourth phase consists of assigning weights to the indicators to combine them into a single sustainability index. Finally, in the fifth phase, the alternatives are evaluated after analyzing all the requirements, criteria and indicators defined in the preceding phases.

2.2 Construction methods

The objective of this case study is to evaluate and compare the sustainability of different construction solutions for low-income housing, including the structural systems of bahareque and conventional concrete. Both alternatives consider a two-story single-family house, featuring 3 frames along the x-axis and 4 frames along the y-axis. The purpose of the structural design was to guarantee the safety and functionality of two construction systems applied to housing: bahareque and reinforced concrete. Their mechanical properties and behavior under gravity and seismic loads were evaluated, following Ecuadorian regulations [NEC-2015 (NEC-SE-CG, 2015) and NEC-DR-BE 2016 (Lopez, 2015)]. The two solutions considered within the scope of this study are described below (Figure 2):

a) Bahareque structural system: This is a construction system that is not usually used but can play a fundamental role in the construction phase due to its local relevance and the use of renewable natural resources. The design of the bahareque system used Guadua cane as the main structural material due

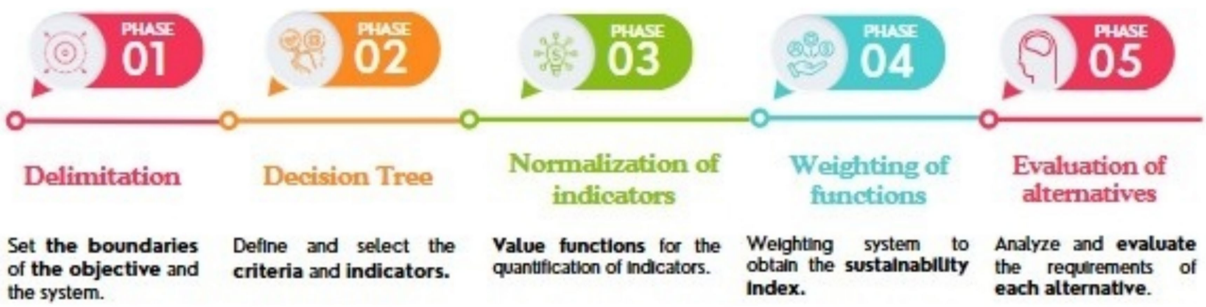

FIGURE 1
Methodological scheme: Integrated Value Model for Sustainable Evaluation (MIVES).

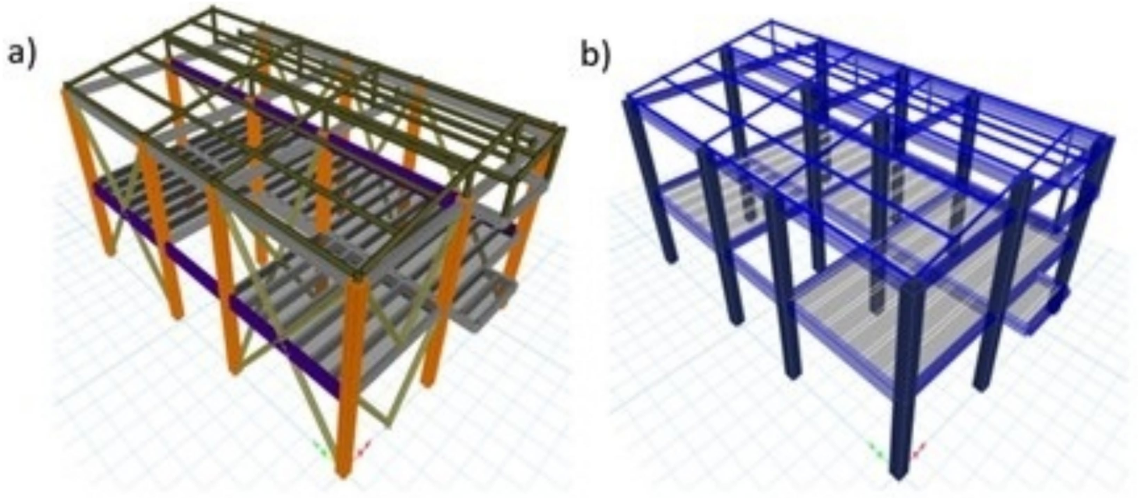

FIGURE 2
Analytical model of each alternative: **(a)** bahareque and **(b)** reinforced concrete (Tello-Ayala and Narvaez-Moran, 2022).

to its sustainable properties and high strength. The guadua cane considered in the design of the house has a compressive strength of 190 kg/cm^2. The beams and columns were composed of hollow sections of Guadua cane, while the foundation consisted of 1.00 × 1.00 m reinforced concrete footings. The columns included four Guadua canes of 0.12 m external diameter and 0.014 m thickness. The structural analysis was also performed using a finite element program, verifying the serviceability limit states and compliance with allowable stresses according to NEC-DR-BE 2016 (Andean Standard for Design and Construction of One and Two-story Houses in Cemented Bahareque) (Lopez, 2015). The fundamental period of vibration was 0.28 s, and the maximum drifts in X-axis (0.008) and Y-axis (0.009) were below the allowable limit of 2% (Tello-Ayala and Narvaez-Moran, 2022).

b) Reinforced concrete structural system: This is the construction system currently most commonly used in residential housing, which comprises a resistant structure with reinforced concrete frames. The design of the reinforced concrete system was based on a detailed analysis using a finite element program, considering beams, columns, and solid ribbed slabs in accordance with ACI 318–19 (ACI, 2019). The material properties included concrete with a compressive strength of 210 kg/cm^2 and A706 gr. 60 reinforcing steel with 4,200 kg/cm^2. The foundation consisted of footings of 1.20 × 1.20 m and 1.30 × 1.30 m with thicknesses of 0.25 m. Serviceability limit states and drifts were verified according to NEC-2015. The maximum vertical deformation was 2.74 mm, amply complying with the allowed limit of 13.21 mm (L/240). Also, the fundamental period of vibration was 0.26 s, and the maximum drifts in X-axis (0.005) and Y-axis (0.01) were within the limit of 2% (Tello-Ayala and Narvaez-Moran, 2022).

2.3 Decision model

The decision model used in this research was developed from the definition of a decision tree based on schemes proposed in previous studies. For its structuring, an exhaustive review of the relevant literature was carried out, with a special focus on the evaluation of sustainability in construction systems. In particular, multi-criteria decision-making models applied to the use of local and non-traditional materials were analyzed (Gilani et al., 2022; Cárdenas-Gómez et al., 2021; Josa et al., 2020; Asensio et al., 2023). The weightings for the requirements, criteria, and indicators, on the other hand, were determined through surveys completed by 20 experts in the field. These surveys provided data that were subsequently analyzed using statistical methods to establish the final weightings for each requirement. The final decision tree (Figure 3) was conducted by combining insights from the literature review with the statistically derived weightings from the expert surveys. The following considerations were taken into account:

- Surveys were designed and administered to experts to determine the weighting of each requirement, criterion and indicator. Participants assigned a percentage of importance to each element based on its relevance within the context of the project.
- The weights assigned to requirements, criteria and indicators were established through structured expert surveys, in which professionals were asked to assign percentage values representing the relative importance of each component. These individual responses were then averaged to obtain the final weights, ensuring a consensus-based representation. This process allowed the construction of a hierarchical decision tree (Figure 3), where the normalized indicators were aggregated according to their assigned weights. The weighting directly influenced the Sustainability Index (SI) by prioritizing the contribution of each criterion—economic, environmental, and social—based on expert judgment, thus enabling a balanced and context-sensitive evaluation.

2.3.1 Economic requirements

In the established decision-making tree, the first requirement (economic) encompasses a single criterion: costs. The associated indicator, construction costs, encompasses the procurement of raw materials, their transportation and manufacture, as well as the

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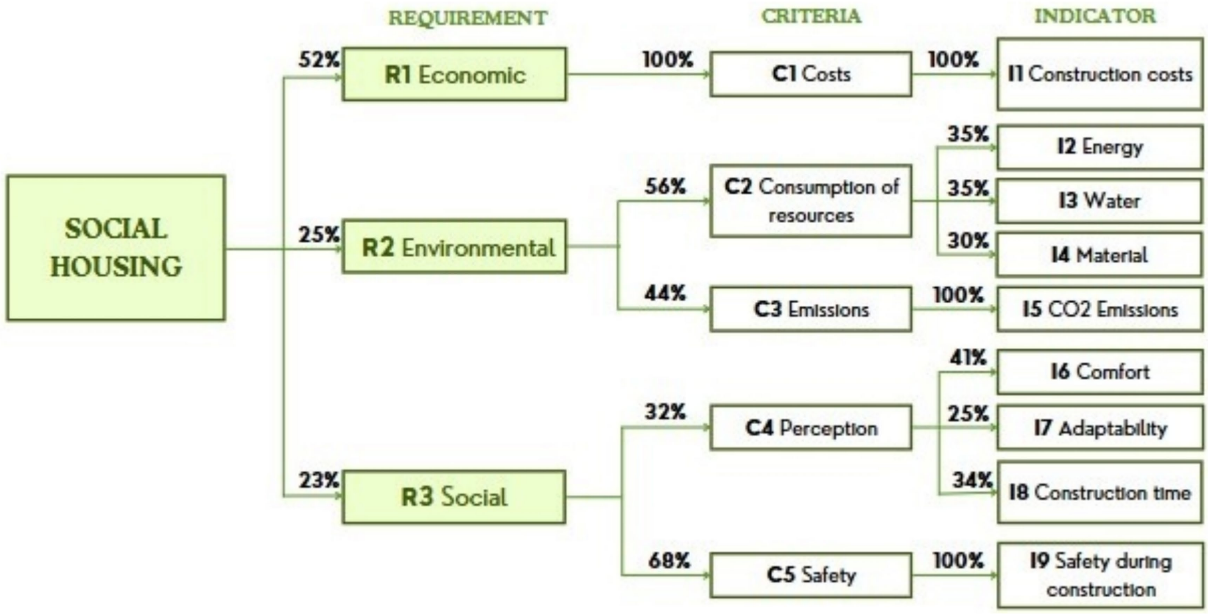

FIGURE 3
Decision tree for social housing.

transportation of construction products to the construction site and the construction of the building. Data pertaining to this indicator were collected from studies that evaluated the costs of the construction of single-family houses with similar construction characteristics and areas (Tello-Ayala et al., 2023; Reyes-quijije et al., 2022). The construction cost indicator adopts a decreasing S-shaped function (DS), as it reflects how economic sustainability progressively decreases as the cost increases.

The structural budget for the houses was made considering a work decomposition scheme that covered from preliminary works to indirect elements. For each structure, the specific activities and materials detailed according to their construction characteristics, guaranteeing the accuracy of the costs. In the case of the bahareque housing, the preliminary phase involved land clearing and earthwork, followed by a structure composed of guadua cane elements such as columns, beams, bracing, and mezzanines. The foundation incorporated footings and block bases, while the roof structure utilized guadua cane purlins with an asphalt coating on wood panels, adapting to the system's unique characteristics. The unit cost analysis considered materials, labor, equipment, and other relevant factors, with labor costs based on the minimum wages established by the State Comptroller General's Office (Tello-Ayala and Narvaez-Moran, 2022).

On the other hand, the reinforced concrete house included similar preliminary activities, such as land clearing and earth moving, but its structural system consisted of concrete and reinforcing steel elements, including footings, braces, columns, beams, ribbed slabs, and stairs. Additionally, a metal roof with fiber-cement was incorporated. Indirect costs accounted for contingencies, designs, and insurance policies (Tello-Ayala and Narvaez-Moran, 2022).

The final budget showed a total cost of $8,488.75 for the bahareque house and $12,909.87 for the reinforced concrete, both with a construction area of 103 m^2 (Tello-Ayala and Narvaez-Moran, 2022). Complete cost estimates, together with quantities of work and unit price analysis, are attached in Supplementary material.

2.3.2 Environmental requirements

The environmental requirement includes two criteria: resource consumption and emissions. Criterion C2 (resource consumption) encompasses three indicators: energy, water and materials, while criterion C3 (emissions) has CO2 emissions as an indicator. As with the preceding indicators, the data for these indicators were derived from studies that considered the production and construction phases of the house thereby obtaining the results of water, energy, and material consumption associated with the construction of the structure, as well as the CO2 emissions it generates. Indicators I2 (energy), I3 (water) and I5 (CO2 emissions) have a decreasing S-shaped function, while I4 (material) considered an increasing linear function (IL).

To determine indicator I2 (energy) and indicator I3 (water), consumption values were obtained from a previous study in reinforced concrete structure with a floor area of 84 m^2 (Reyes-quijije et al., 2022). These values were adjusted proportionally to the 103 m^2 surface area of the structure analyzed in the present study, thus ensuring that the environmental indicators accurately reflect the characteristics and scale of the case study.

Indicator I4 (material) was evaluated through surveys, considering three fundamental aspects: the scarcity of raw materials, the potential for recycling, and the incorporation of recycled materials (Josa et al., 2020). Each of these criteria was assessed using a scale from 1 to 3, where 1 indicates insufficient compliance, 2 represents moderate compliance, and 3 corresponds to excellent compliance.

In the case of the bahareque system utilized guadua cane, recognized for its sustainability and ecosystemic benefits, though requiring chemical treatments to enhance its durability against external factors. In contrast, reinforced concrete incorporated materials such as cement, water, sand, gravel, and steel, primarily sourced from local suppliers.

For indicator I5 (CO_2 emissions), a comparative life cycle assessment (LCA) of both construction systems: Bahareque and reinforced concrete were carried out. This analysis aimed to determine the amount of carbon incorporated in each structural phase, from manufacture to construction, and to evaluate which of the two options is more sustainable in terms of carbon emissions, in line with international sustainability standards. The analysis focused on the structural phases of each building system, considering a 40-year lifespan. Phases between A1 and A5 were evaluated, ranging from the manufacture of materials (A1-A3), their transportation to the construction site (A4) and the waste generated during the construction process (A5). The scope included only structural elements and associated embodied carbon emissions (Tello-Ayala and Narvaez-Moran, 2022).

2.3.3 Social requirements

The social requirement is evaluated through two criteria: perception and safety. Criterion C5 (perception) included three indicators: comfort, adaptability, and construction time; while criterion C6 (safety) incorporates a single indicator that assessed safety during construction. The data for these indicators were obtained through surveys conducted with 20 experts in the field. Indicators I6 (comfort), I7 (adaptability), and I9 (safety during construction) adopted a linear increasing function, while indicator I8 (construction time) considered a linear decreasing function (DL).

For the evaluation of indicator I6 (comfort), two fundamental aspects were considered: the of the structural element and the warmth of the material (Josa et al., 2020).

The survey aimed to compare the bahareque and reinforced concrete construction systems based on social and construction-related criteria. This evaluation sought to determine how well each system met the requirements for affordable housing. Participants rated various aspects of each structural system using a scale from 1 to 3, where 1 indicated insufficient compliance, 2 moderate compliance, and 3 excellent compliance. The evaluated criteria social perception, safety, and construction time, considering factors such as the use of recycled materials, adaptability to local contexts, and safety during the construction process. The mode of the responses was ultimately used, as it provided the most coherent results for the aspects under analysis.

2.4 Parameters of value functions

Once the form of the value functions was determined according to the nature of each indicator, the parameters defining these functions were established, as detailed in Table 1. The corresponding graphs can be examined in Supplementary material for further analysis.

The definition of these value functions was based on a comprehensive literature review to obtain the necessary parameters. The reviewed studies focused on structures similar to two-story single-family dwellings with comparable construction areas, analyzing key aspects such as budget, resource consumption, and carbon footprint (Tello-Ayala and Narvaez-Moran, 2022; Reyes-quijije et al., 2022; Remigio, 2016). Furthermore, for social indicators, the parameters were established ensuring a data-driven approach that reflects the perspectives of professionals in the field.

2.5 Quantification of indicators

The sustainability index calculation was based on the data presented in Table 2. The corresponding data were obtained for each indicator according to the analysis previously performed in sections 2.3.1., 2.3.2., and 2.3.3.

2.6 Sensitivity analysis

To evaluate the robustness and reliability of the results obtained, a sensitivity analysis is performed, which consists of proposing variations in the weights or value functions defined in the decision model to observe the behavior of how these changes affect the final result and the ranking of alternatives (Viñolas Prat et al., 2009). These changes are necessary to consider different factors that affect decision making, such as: customs, geographic location and project requirements (Asensio et al., 2023).

Due to the focus of the research and previous studies, four scenarios were considered in this evaluation. The first scenario assigns equal weight to the three requirements (economic, environmental, and social). In the second scenario, the weight of the economic requirement is 70%, while the environmental and social requirements have a weight of 15% each. In the third scenario, the environmental requirement receives 70% of the weight, leaving 15% for the other two. Finally, in the fourth scenario, the social requirement is prioritized

TABLE 1 Parameters defined for the value functions of each indicator.

Indicators	Unit	Function	X_{min}	X_{max}	C	K	P
I1. Construction costs	$	DS	55,000	0	50,000	2.5	4
I2. Energy	MJ	DS	1,100,000	0	190,000	0.1	2
I3. Water	m^3	DS	350	0	140	0.1	2.5
I4. Material	Points	IL	3	9	1	0	1
I5. CO_2 emissions	Kg CO_2	DS	100,000	0	300,000	0.1	2.5
I6. Comfort	Points	IL	2	6	1	0	1
I7. Adaptability	Points	IL	1	3	1	0	1
I8. Construction time	Points	DL	3	1	1	0	1
I9. Safety during construction	Points	IL	1	3	1	0	1

TABLE 2 Data for sustainability assessment.

Indicators	Unit	Bahareque structure	Reinforced concrete structure
I1. Construction costs	$	8488.75	12909.87
I2. Energy	MJ	946.93	946.93
I3. Water	m^3	25.94	25.94
I4. Material	Points	9	7
I5. CO_2 emissions	Kg CO_2	25	94
I6. Comfort	Points	5	6
I7. Adaptability	Points	2	3
I8. Construction time	Points	3	2
I9. Safety during construction	Points	3	2

with a weight of 70%, while the economic and environmental requirements receive 15% each.

3 Results

3.1 Global sustainability

Figure 4 shows the results of the Sustainability Index for the bahareque and reinforced concrete systems. The bahareque system achieved a higher index (0.88) compared to reinforced concrete (0.75), reflecting its better performance in terms of construction costs, lower environmental impact, and social advantages. In the breakdown by indicators, bahareque stood out especially in construction costs, CO_2 emissions, thermal comfort and adaptability. For its part, reinforced concrete showed strengths in safety during construction and in the availability of more industrialized materials.

In terms of the economic component, the bahareque system was more efficient, with a contribution of 49.6% to the total index. This result is due to its low implementation and maintenance costs, which are reflected in the use of local materials and a less expensive construction process. In particular, the cost analysis shows that the structural elements of bahareque represent 38% less compared to the reinforced concrete alternative (Supplementary material). Likewise, under the heading of roofing, there is a 29% reduction in the final budget of the bahareque, attributed to the use of Guadua cane purlins in its structure.

On the other hand, the reinforced concrete system presented a greater economic impact, with a contribution of 50.7% to the total index, mainly influenced by the high cost of industrial materials and the need for specialized labor. This effect was reflected in the budget, particularly in the reinforcing steel item, where costs were up to four times higher compared to the bahareque structure. Similarly, structural steel, which is widely used in this type of building, represents a determining factor in the increase of the total cost of reinforced concrete.

In the environmental criterion, the bahareque system stood out, with a contribution of 28.5% to the total index, due to its low environmental impact derived from the use of local materials, such as guadua cane. This characteristic is fundamental for its sustainability, since it allows a significant reduction of CO_2 emissions. The results of the Life Cycle Analysis (LCA) evidenced that the bahareque structure generated only 27% of the embodied carbon compared to the reinforced concrete house.

In contrast, the reinforced concrete system presented a larger ecological footprint, with a contribution of 30.7% in the environmental index. This impact is attributed to the use of industrialized materials, which generate high CO_2 emissions. In particular, the manufacturing phase was the most critical in terms of carbon emissions for both structures. In the case of bahareque, this stage accounted for 66% of total emissions, while in reinforced concrete it reached 90% (Tello-Ayala et al., 2023).

In social terms, the bahareque system obtained a contribution of 21.9%, reflecting greater acceptance in the surveys due to its shorter execution times and reduced risks during construction. In contrast, reinforced concrete presented a social contribution of 18.6%, standing out mainly for its esthetic value perceived by users and its adaptability to different construction contexts worldwide. Its wide use around the world supports its versatility and acceptance within the construction industry.

These results allow stating that bahareque construction generates significantly lower carbon emissions than reinforced concrete, as illustrated in Figure 5. The embodied carbon of bahareque was 25 $kgCO_2e/m^2$, representing only 27% of the embodied carbon in reinforced concrete. In reinforced concrete, the manufacturing phases accounted for approximately 90% of the total emissions, while in bahareque these phases contributed 66% (Tello-Ayala et al., 2023). These findings establish bahareque as a more sustainable structural alternative, aligning with emission reduction targets set by international organizations such as LETI (201 $kgCO_2e/m^2$) (LETI, 2020) and RIBA (144 $kgCO_2e/m^2$) (RIBA, 2021).

In addition, regarding the structural performance of both systems, it was found that both complied with the deformation and drift regulations established in NEC-2015. However, the reinforced concrete presented greater stiffness, with a maximum deformation of 2.74 mm compared to that of the bahareque. As for drifts, the maximum values were lower in the reinforced concrete (0.005 in X-axis and 0.01 in Y-axis) compared to the bahareque (0.008 in X-axis and 0.009 in Y-axis). This reflects the more flexible nature of the bahareque (Tello-Ayala and Narvaez-Moran, 2022).

3.2 Sensitivity analysis

The results of the sensitivity analysis, presented in Figure 6, show that the bahareque structural system maintains a higher sustainability index (SI) in all the scenarios analyzed. In the equal weight's scenario, the bahareque achieved an SI of 0.89, while reinforced concrete achieved 0.76. In the scenario with the highest economic weight, bahareque retained its advantage with an IS of 0.88, compared to reinforced concrete with 0.74. When the environmental requirement is prioritized, bahareque showed a significant increase in its SI, reaching 0.94, while the reinforced concrete also improved, achieving 0.85. In the last scenario, with a predominant social weight, bahareque obtained an IS of 0.85, again surpassing reinforced concrete, which decreased to 0.67.

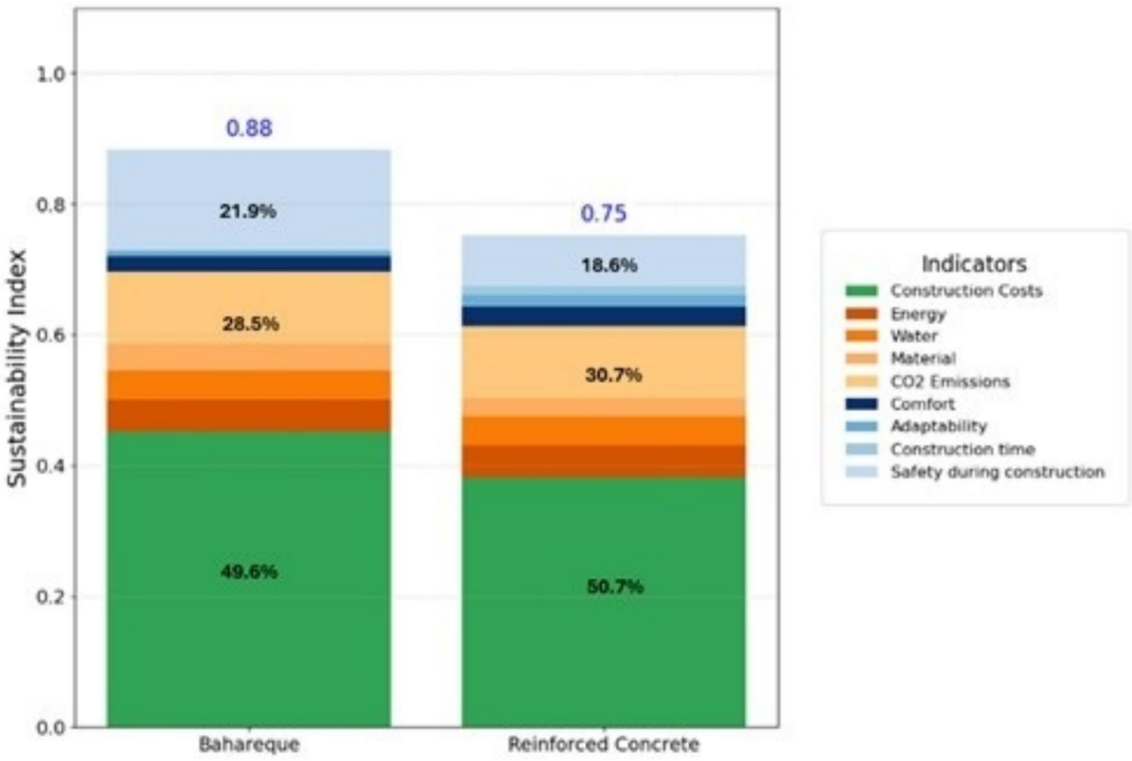

FIGURE 4
Results of sustainability index with the contribution of each indicator.

It is relevant to emphasize that, in the third scenario, the bahareque system reached an outstanding value of 0.94. This result is attributed to the nature of the value functions and the parameters that determine them, which highlights the importance of adjusting these parameters according to the specific objectives of the research and the context in which it is carried out. A detailed explanation of the formulation and influence of these parameters is provided in Supplementary material.

These results confirm the robustness of the bahareque structural system in terms of sustainability, standing out especially in the scenarios where environmental and social requirements are prioritized. On the contrary, reinforced concrete showed a more notable decrease in its sustainability index in the scenarios where environmental or social requirements have greater weight, which reflects its greater environmental impact and lower social benefits in comparison with bahareque.

4 Discussion

The results obtained in this study reflect the superior sustainability performance of the bahareque system (0.88), compared to reinforced concrete (0.75). This trend coincides with previous studies that have evaluated other sustainable construction solutions. For example, research on reinforced adobe techniques for reconstruction in Andean seismic zones has reported sustainability indices of 0.714 and 0.709 for systems with reed reinforcement and tie ropes, respectively (Cárdenas-Gómez et al., 2021). These values, although relatively high, remain below the index obtained for reinforced concrete in this study (0.75). This may be due to the specific weighting and criteria applied in the MIVES model, which can favor reinforced concrete in certain sustainability dimensions, such as structural safety or long-term performance. However, both remain below the performance level of bahareque, which stands out for its balance between low environmental impact, economic accessibility and adaptability to local conditions is required.

Furthermore, reinforced concrete, although widely used in the construction industry, has disadvantages in terms of sustainability. To contextualize its performance further, we refer to previous studies on steel truss systems, which, while more commonly used in industrial or large-scale structures, illustrate the lower bounds of sustainability scores among structural materials. Specifically, previous studies have determined that steel trusses have sustainability indices of 0.57 for flat trusses and 0.53 for inclined trusses (Josa et al., 2020), values significantly lower than both bahareque and reinforced concrete. While steel is a recyclable material, its production process generates high CO_2 emissions. Although steel trusses are not typically used in small-scale residential buildings, their inclusion in the comparison highlights the wider spectrum of structural alternatives and reinforces the positioning of bahareque as a more environmentally and economically favorable option.

On the other hand, due to the lower amount of steel reinforcements used in the bahareque structure (Supplementary material), compared

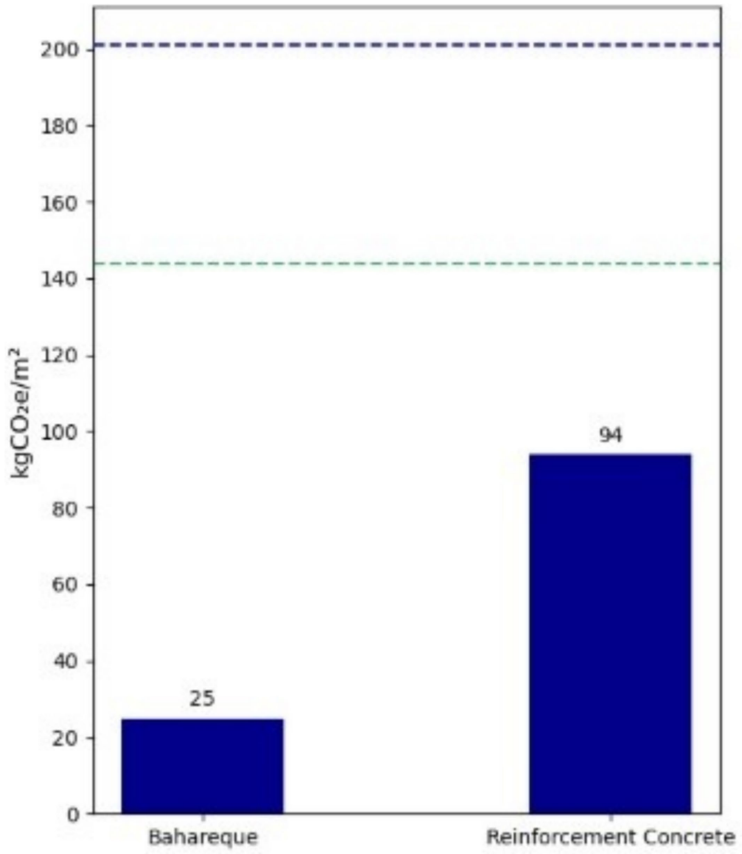

FIGURE 5
Comparison of carbon emissions from both structural systems (Tello-Ayala et al., 2023).

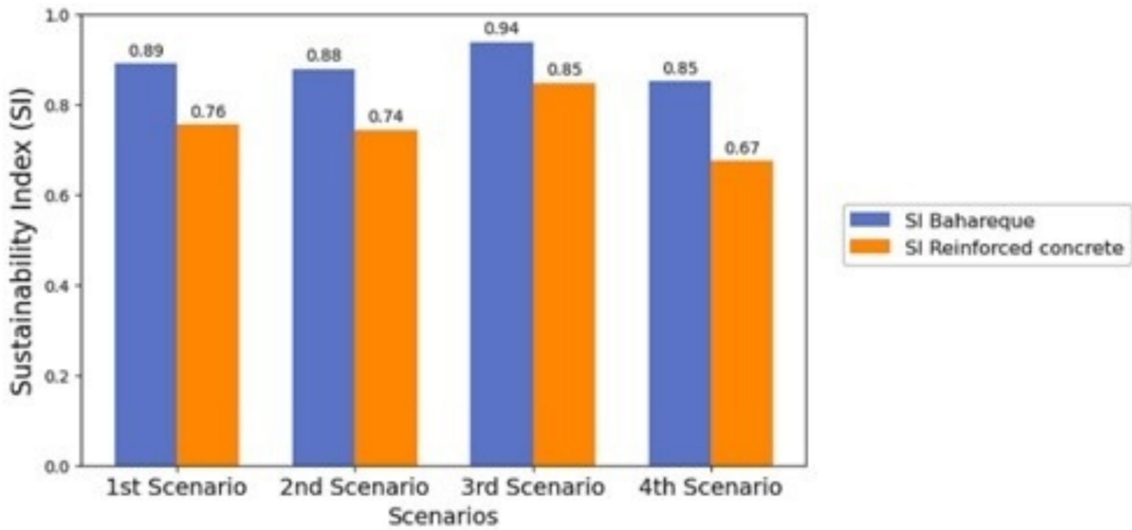

FIGURE 6
Sensitivity analysis results.

to conventional materials such as reinforced concrete, it is a viable alternative to reduce the carbon footprint of the construction industry. However, its large-scale adoption requires technical dissemination strategies and strengthening of local capacities, and better control in informal constructions, which affects the structural quality and social perception of this material (Llumiquinga, 2023).

Finally, it is necessary to consider the regulatory framework and legal requirements for construction in each country or region. The regulation of alternative techniques, such as bahareque, may represent an obstacle to their massive implementation. In this sense, collaboration between governments, universities and specialized organizations is recommended to develop proposals that encourage public policies aimed at promoting sustainable construction materials and techniques, as is the case in Colombia with the Guadua Law (2022), which establishes that at least 30% of rural housing financed by the government should be built with bamboo (Min Vivienda, 2022).

5 Conclusion

This study aimed to evaluate the sustainability performance of two structural systems—bahareque using Guadua cane and conventional reinforced concrete—for social housing in Ecuador. For this purpose, the Multi-Criteria Decision-Making framework MIVES was used, integrating economic, environmental, and social indicators.

The scope of the study covered a typical two-story social housing unit, that complies with national safety and functionality standards. Data were collected from cost analyses, literature, and expert surveys and then normalized using specific value functions. Additionally, a sensitivity analysis with varying weighting scenarios was conducted to ensure the robustness of the results.

Based on the results' analysis and discussions presented, the following conclusions can be drawn:

The use of bahareque (0.88) for the construction social housing units designed led to a SI 17.5% greater to that achieved by the reinforced concrete alternative (0.75).

Bahareque offers significant cost reductions—up to 38% savings on structural elements and 29% on roofing—due to its reliance on locally sourced materials and simpler construction processes.

With only 27% of the CO_2 emissions produced by reinforced concrete, bahareque presents a markedly lower environmental footprint, largely due to less energy-intensive material processing and reduced transportation requirements.

The system based on the use of bahareque showed advantages in construction speed and adaptability to local conditions, although reinforced concrete maintained slightly higher scores in construction safety and material standardization.

Sensitivity analysis confirmed that bahareque maintains its sustainability performance advantages under various weighting scenarios, whether economic, environmental, or social aspects are prioritized.

It must be emphasized that these findings are context-specific, as variations in local material availability and regional construction practices could influence sustainability outcomes. Likewise, the assessment was based on data from selected case studies and expert surveys, which may not fully capture all regional differences or long-term performance factors.

Future research should explore the scalability of bahareque systems in diverse geographical settings and investigate the feasibility of hybrid construction methods that combine traditional and modern materials. Additionally, further studies should examine the long-term durability, maintenance requirements, and regulatory challenges associated with bahareque, as well as to refine the weighting parameters in the MIVES model by incorporating broader stakeholder perspectives.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AR-T: Formal analysis, Visualization, Writing – original draft, Writing – review & editing, Investigation. NG-T: Methodology, Conceptualization, Writing – review & editing, Investigation, Writing – original draft, Supervision, Funding acquisition, Visualization, Resources, Validation, Formal analysis, Project administration. IJ: Supervision, Methodology, Project administration, Writing – review & editing, Resources, Writing – original draft, Visualization. AF: Project administration, Supervision, Writing – original draft, Conceptualization, Visualization, Writing – review & editing, Resources.

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Conflict of interest

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsc.2025.1634678/full#supplementary-material

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