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Evaluating the sustainability performance of sustainable, innovative, and affordable housing

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ABSTRACT

The provision of sustainable, innovative, and affordable housing (SIAH) is a global priority, especially in rapidly urbanizing contexts. However, a comprehensive tool for assessing the sustainability performance of such housing is lacking. This study develops the SIAH Sustainability Assessment Tool (SIAH-SAT), integrating 127 validated critical success factors (CSFs) across four dimensions: economic, environmental, social, and technical. Using an exploratory mixed-method design, a Delphi process and Analytic Hierarchy Process (AHP) survey with international experts validated the CSFs and established relative sustainability weights (RSWs). The tool was applied to five diverse affordable housing cases, producing Sustainability Index (SI) scores that highlighted strengths and areas for improvement. Results demonstrate SIAH-SAT's capacity to evaluate and compare housing performance across subcategories, offering a context sensitive framework for policymakers, developers, and practitioners. By supporting evidence-based decision-making, SIAHSAT advances scientific discourse on sustainable, inclusive urban development and guides the delivery of housing aligned with global sustainability goals.

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AHP; affordable housing; sustainability assessment; sustainability index; innovation

1. Introduction

Sustainable development has been adjudged crucial for global advancement (WGBC 2024). However, society's sustainability aspirations remain bedeviled by challenges associated with climate change and increasingly unsustainable production and consumption patterns. Scholars have attributed a significant proportion of these challenges to processes associated with the delivery, operation and decommissioning phases of the built environment (Awuzie, Ngowi, and Aghimien 2024). The built environment remains a

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major contributor to sustainable livelihood of the global populace as it provides services ranging from shelter to hosting economic opportunities, despite serving as a domicile for a multiplicity of anthropogenic activities (Mouratidis 2021). The provision of shelter, an integral part of the built environment, has continued to pose a challenge to successive governments, globally (Pomponi et al. 2019). This is particularly as it pertains to the delivery and management of sustainable and affordable housing (Mahachi, Moghayedi, and Michell 2023). Therefore, society's attempts at meeting the burgeoning demand for housing must prioritize sustainability and affordability considerations, hence rendering it an increasingly complex endeavor.

The quest to reduce the incidence of these challenges has culminated in the demand for improved sustainability performance of the built environment (Cotella et al. 2025). This demand has catalyzed a positive paradigm shift in the construction industry, particularly in housing projects. This shift has resulted in the emergence of sustainability-oriented innovations encompassing new designs, innovative housing elements and materials, modern construction methods and building technologies (Adabre and Chan 2019; Moghayedi et al. 2021). These sustainability-oriented innovations have been identified as key mechanisms for reducing lifecycle emissions and costs, improving quality and processes, and enhancing the environmental and social aspects necessary for market continuity within the housing sub-sector of the construction industry (Dok-Yen, Duah, and Addy 2023; Moghayedi and Awuzie 2025).

Scholars emphasize the need for a deep understanding of the critical success factors (CSFs) in affordable housing and their impact on housing sustainability, which directly affects the performance, efficiency, affordability and sustainability of houses and consequently, cities and societies (Bhyan, Shrivastava, and Kumar 2023; Moghayedi et al. 2021). Knowing how design techniques, housing elements, construction methods, and technologies impact housing sustainability performance is imperative. This knowledge empowers industry players to select and utilize optimal housing components in a way that engenders improved sustainability performance of SIAH delivery and management (Moghayedi et al., 2022).

Although the affordable housing sector has witnessed increased implementation of these sustainability-oriented innovations, the effect of such deployment on housing sustainability performance is yet to be properly articulated. This is due to the lack of comprehensive tools to measure housing sustainability performance of affordable housing projects (Adamec, Janoušková, and Hák 2021). The lack of an efficient systematic approach for evaluating the performance of these sustainability-oriented innovations constitutes a challenge to relevant stakeholders regarding the selection of the most sustainable and innovative design techniques, construction methods, and building materials to adopt (Bhyan, Shrivastava, and Kumar 2023; Moghayedi et al. 2021). Without a comprehensive sustainability assessment tool, innovations may be adopted inappropriately, lacking the necessary scientific foundation to ensure their efficiency and effectiveness. This can significantly impact the sustainability performance of affordable housing projects and, consequently, the quality of life for residents.

In response to the need for a comprehensive sustainability assessment of affordable housing projects, this study seeks to detail the development of a dynamic SIAH assessment tool (SIAH-SAT).

By systematically reviewing the most common and comprehensive Building Sustainability Assessment Systems (BSAS) and frameworks for buildings and housing and applying an advanced Multi-Criteria Decision-Making method, SIAH-SAT enables a structured and quantitative assessment of the relative sustainability weights of 127 identified CSFs for affordable housing. The result is a comprehensive index that evaluates the sustainability performance of affordable housing delivery and management.

This index serves as a critical metric for comparing the sustainability performance of different housing designs and technologies, guiding the development of more sustainable and affordable housing solutions. Subsequently, SIAH-SAT will be validated through a robust application within various case studies in this study. This validation underscores the effectiveness of the SIAH-SAT in providing a wholesome evaluation of affordable housing sustainability performance, considering the impact of the design, materials, construction methods, and innovative technologies.

To achieve its aim, this study addresses several research objectives:

a. First, to determine the relative sustainability weight of four main housing components – design, element, method, and technology – and their 127 CSFs using the advanced and reliable AHP method.
b. Second, to develop a dynamic SIAH sustainability assessment tool (SIAH-SAT), and;
c. Lastly, to validate the emergent SIAH-SAT through its application to various cases.

It is expected that the anticipated outcome of this study, a comprehensive dynamic SIAH-SAT, will enable stakeholders to choose the optimal housing components and sustainability-oriented innovations to deploy in their quest for optimal levels of sustainability performance. Also, it will aid housing designers, developers, policymakers, and end-users in developing and managing SIAHs.

This study's novelty lies in the integration of multidisciplinary indicators of housing sustainability into a single, comprehensive SAT for affordable housing. Additionally, this research introduces a new sustainability index (SI) tailored to affordable housing projects for the first time, enabling a more nuanced and accurate comparison of different housing designs and innovative technologies, thereby addressing a gap in existing SATs. Furthermore, it is the first sustainable and affordable housing SAT which considers all sustainability facets inclusive of the technical sustainability aspects of affordable housing in a systemic manner, thereby engendering cleaner production. The development of the SIAH-SAT provides a practical tool for stakeholders, enhancing their ability to make data-driven decisions that support the creation of sustainable and affordable living environments, and thereby contributing to broader sustainable development goals and beyond.

2. Literature review

2.1. Overview of housing sustainability

Housing remains a fundamental human necessity, with far-reaching implications for well-being, education, societal stability, economic productivity, and public health

(Ichendu and Budnukaeku 2021; UN-Habitat 2021). However, to fulfil these roles effectively, housing must be both sustainable and affordable (Galster and Lee 2021). While the term 'sustainable housing' is generally associated with reducing energy use, minimizing greenhouse gas emissions, and promoting resource efficiency (IEA 2023), its interpretation and practical application vary considerably across different global contexts – particularly between the Global North and Global South.

In the Global North, sustainable housing practices are largely driven by environmental concerns and efforts to reduce the ecological footprint of existing building stocks (Moore and Doyon 2023). Policies often prioritise retrofitting older housing units and enforcing stringent energy-efficiency standards. Conversely, in the Global South, the challenges are more closely linked to rapid urbanisation, housing shortages, and the proliferation of informal settlements issues often exacerbated by conflict, rural-to-urban migration, and climate change (Cotella et al. 2025). These contrasting realities highlight the necessity for context-sensitive approaches to sustainability that address the specific barriers and opportunities in each region.

Key sustainability issues affect housing globally, albeit with varying degrees of severity and scope. One of the most critical concerns is energy efficiency. Residential buildings currently account for approximately 24% of global energy consumption (UNEP 2024), making energy-saving strategies essential. While energy retrofitting and smart energy systems are widely promoted in the Global North, the Global South faces limitations in technical capacity and financial resources, hindering the integration of energy-efficient technologies (IEA, 2021). This is also strongly linked to the issues of housing costs and affordability. Rising housing costs relative to income contribute to housing insecurity, with adverse effects on health, social integration, and economic mobility (WGBC 2024). The Global South is disproportionately affected by housing shortages, leading to the expansion of informal settlements (UN-Habitat 2019), whereas the Global North contends with gentrification, increasing property prices, and growing inequality leading to the environmental sustainability concerns (UN-Habitat 2021), shaped by the materials used and waste generated during construction. The Global South often emphasises the use of locally sourced or traditional materials to balance cost and environmental impact, while the Global North has seen a movement towards sufficiency-oriented designs and minimalist construction to reduce material overuse (Moore and Doyon 2023; WGBC 2024).

In addition to the above, social equity remains a fundamental dimension of sustainable housing. In the Global South, limited access to basic services and infrastructure in low – and middle-income housing exacerbates inequality. Meanwhile, the Global North faces ongoing challenges related to housing discrimination and disparities in housing quality and accessibility (UN-Habitat 2021). Addressing these issues requires integrated policies that combine technical solutions with a commitment to social justice and inclusion. The integration of technology to address societal challenges is valuable here. While smart technologies for energy management and environmental monitoring are increasingly common in the Global North, adoption in the Global South is often limited by infrastructural and economic constraints (IEA, 2021). This socio-technological divide restricts access to innovation-driven sustainability benefits in many low-income settings leading to the policy and governance attributes. Policy structures in the Global North such as green building standards and financial incentives support the implementation of sustainable practices (EEA 2024). In contrast, many countries in the Global South lack comprehensive sustainability frameworks or effective enforcement mechanisms, underscoring the need for institutional strengthening and policy innovation (UN-Habitat 2019).

Innovation in construction methods presents both challenges and opportunities across regions. Despite the availability of advanced technologies, many housing developments continue to rely on conventional approaches, limiting sustainability gains. As noted by Adabre et al. (2020) and Moghayedi and Awuzie (2025), scaling up the adoption of modern methods of construction, such as prefabrication, modular systems, and green materials, is essential for transforming housing sustainability outcomes globally. Coming back to the limitations in housing sustainability and affordability efforts is the focus on upfront costs at the expense of lifecycle considerations. As argued by Larsen et al. (2022), this short-term perspective often leads to increased long-term energy use and maintenance costs. Adopting a lifecycle cost approach can support the design and implementation of housing that is both economically and environmentally sustainable over time.

From the foregoing, it can be discerned that housing sustainability is influenced by a complex interplay of environmental, economic, social, and technical factors, which vary substantially between the Global North and South. These differences underscore the need for flexible, contextually relevant strategies that integrate sustainability and affordability. By adopting holistic, lifecycle-based, and inclusive approaches, stakeholders can contribute meaningfully to achieving more sustainable and equitable housing systems, aligned with the broader aims of the Sustainable Development Goals (SDGs).

2.2. Overview of housing sustainability assessment tools and methodology

SATs play a pivotal role in the building sector by facilitating the selection of optimal designs, methods, materials, and technologies that enhance sustainability across economic, environmental, social and technical dimensions (Adamec, Janoušková, and Hák 2021). These tools provide structured frameworks to evaluate and compare the sustainability performance of various building projects, guiding stakeholders in making informed decisions (Lazar and Chithra 2020). By considering factors such as energy efficiency, resource use, environmental impact, and social equity, these assessments promote the development of buildings that are not only cost-effective and durable but also environmentally friendly (Adamec, Janoušková, and Hák 2021). Moreover, SATs aid in meeting regulatory requirements, achieving green building certifications, and aligning with the UN SDGs (Srivastava, Iyer-Raniga, and Misra 2024).

While numerous tools have been developed to assess the sustainability of buildings, the majority are tailored for non-domestic buildings, with limited coverage of housing projects, especially those geared towards affordability (Lazar and Chithra 2020). This section reviews most widely recognized Building Sustainability Assessment Systems (BSAS) and framework comprising of building SATs and certification systems, examining their strengths, limitations, and applicability across diverse housing contexts. Special attention is given to their effectiveness in promoting sustainable practices within affordable housing projects, highlighting gaps in current methodologies and exploring opportunities for enhancing their relevance in the housing sector.

Accordingly, this study focuses on five internationally recognized tools – LEED, BREEAM, CASBEE, Green Star, and DGNB – due to their comprehensive, multi-dimensional frameworks and their relevance to both environmental and affordability considerations in housing. These tools are widely adopted across different regions, offer transparent methodologies, and support the evaluation of social, economic, and environmental sustainability, aligning well with global policy agendas such as the UN SDGs. In contrast, tools like Green Mark, Green Ship, and HK BEAM were not included, as they are primarily region-specific with limited applicability beyond their national contexts and narrower coverage of social sustainability aspects, making them less suitable for global comparative analysis in the affordable housing sector.

- *LEED (Leadership in Energy and Environmental Design)* is one of the most widely recognized and adopted green building certification systems globally. Its comprehensive coverage spans site development, water savings, energy efficiency, materials selection, and indoor environmental quality, making it applicable to various building types and sizes, including residential projects. However, LEED's certification costs and complexity pose significant barriers to its deployment to affordable housing projects. The process can be expensive and resource-intensive, requiring substantial documentation and professional expertise (Mahmoud, Zayed, and Fahmy 2019). LEED encompasses nine major categories, with over 80 specific criteria. LEED places a strong emphasis on environmental sustainability, a moderate emphasis on economic aspects, and a limited focus on social sustainability (LEED 2022). While LEED does support the integration of innovative solutions to some extent, its primary focus remains on environmental factors.
- *BREEAM (Building Research Establishment Environmental Assessment Method)* offers a comprehensive and flexible approach to sustainability assessment, covering a wide range of issues and allowing customization to local contexts. It encourages early integration of sustainability considerations and incorporates lifecycle impacts of building components (Mahmoud, Zayed, and Fahmy 2019). Despite these strengths, BREEAM certification can be costly and complex, posing challenges for affordable housing. Additionally, while flexible, BREEAM may require significant adaptation for specific regional needs in affordable housing. BREEAM includes ten categories, with over 50 specific criteria. It strongly emphasizes environmental sustainability, with moderate consideration for economic aspects and innovation, and limited focus on social sustainability.
- *Green Star* provides a holistic approach to sustainability, addressing a broad spectrum of aspects, and is particularly adapted to suit specific regional conditions in Australia. It includes social and economic factors alongside environmental criteria, making it more comprehensive than some other tools. However, the implementation cost and compliance requirements can be high hence impacting affordability (Lazar and Chithra 2020). Additionally, while adaptable, Green Star is primarily tailored for the Australian market, which may limit its applicability, particularly in regions such as the Global South. Green Star assesses nine categories with over 70 specific criteria.

It places a strong emphasis on environmental sustainability, with moderate consideration for both economic and social sustainability, and moderate support for innovation.

- *CASBEE (Comprehensive Assessment System for Building Environmental Efficiency)* focuses on a comprehensive evaluation of environmental performance, using Building Environmental Efficiency (BEE) indicators for assessment. Despite its strengths, CASBEE's complex methodology can be challenging for affordable housing projects (Mahmoud, Zayed, and Fahmy 2019). Moreover, being primarily developed for the Japanese context, its applicability in other regions might be limited. CASBEE assesses five categories, with over 50 specific criteria. It strongly emphasizes environmental sustainability, with moderate consideration for economic aspects, limited focus on social sustainability, and limited support for innovation.
- *DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen)* takes an integrated approach to sustainability assessment, balancing environmental, economic, and sociocultural aspects. It has a strong focus on lifecycle costs and performance, making it adaptable to different building types and scales, including residential buildings. However, the high certification costs and extensive documentation requirements can hinder its application in affordable housing projects (Lazar and Chithra 2020). DGNB includes six categories, with over 60 specific criteria. It places a strong emphasis on all three pillars of sustainability, with moderate support for innovation.

While existing SATs offer comprehensive frameworks for evaluating the sustainability of buildings, they vary and are limited in their applicability to affordable housing projects. Tools like DGNB offer a balanced focus on environmental, economic, and social sustainability but may pose cost and complexity challenges. LEED and BREEAM are well-recognized but also expensive and complex, which can be prohibitive for affordable housing projects. Green Star and CASBEE, whilst focusing primarily on specific regions, offer region-specific advantages but may require adaptation for broader use. Therefore, developing or adapting SATs to better address the specific needs of affordable housing projects, particularly in diverse geographic contexts, remains a critical area for future research and development.

The Sustainable Innovative and Affordable Housing (SIAH) framework developed by Moghayedi et al. (2021) is specifically designed to address the unique challenges of affordable housing. This framework encompasses 127 CSFs categorized under four main areas: housing design, housing elements, building methods, and technologies. Each of these categories is further divided into four subcategories of economic, environmental, social and technical sustainability respectively. This comprehensive structure ensures that the SIAH framework adequately covers all three pillars of sustainability but also technical specifications. The SIAH framework is designed to be holistic, integrating a broad spectrum of factors that influence the sustainability of affordable housing projects. Unlike the existing tools, which may emphasize environmental sustainability while offering limited coverage of social and economic aspects, SIAH ensures a balanced consideration of all three pillars (Moghayedi et al. 2021).

SIAH includes CSFs related to energy efficiency, material selection, and waste management, ensuring minimal environmental impact. The framework addresses lifecycle costs,

Table 1. Review of the most common building Sustainability Assessment Tools and SIAH framework.

Specification	LEED	BREEAM	Green Star	CASBEE	DGNB	SIAH
Geographical area	Global	Global	Australia	Japan	Germany	Global
Categories	9 *(Location & Transportation, Sustainable Sites, Water Efficiency, Energy & Atmosphere, Materials & Resources, Indoor Environmental Quality, Innovation, and Regional Priority)*	10 *(Management, Health & Wellbeing, Energy, Transport, Water, Materials, Waste, Land Use & Ecology, Pollution, and Innovation)*	9 *(Management, Indoor Environment Quality, Energy, Transport, Water, Materials, Land Use & Ecology, Emissions, and Innovation)*	5 *(Energy Efficiency, Resource Efficiency, Local Environment, Indoor Environment, and Management)*	6 *(Environmental Quality, Economic Quality, Sociocultural and Functional Quality, Technical Quality, Process Quality, and Site Quality)*	4 *(Design, Element, Method, Technology) 16 subcategories (Economic, Environment, Social, Technical)*
Number of factors	89	55	74	67	37	127
Focus Area	New Residential Single Family	New building & Refurbishment	New house	New house and Renovation	New building and renovation	New affordable house and renovation
Applicability to Affordable Housing	Moderate	Limited	Moderate	Moderate	Limited	High
Emphasis on economic sustainability	Moderate	Moderate	Moderate	Moderate	Strong	Strong
Emphasis on environmental sustainability	Strong	Strong	Strong	Strong	Strong	Strong
Emphasis on social sustainability	Limited	Limited	Moderate	Limited	Strong	Strong
Emphasis on technical aspects	Limited	Limited	Limited	Limited	Limited	Strong
Emphasis on innovation	Moderate	Moderate	Moderate	Limited	Moderate	Strong

affordability, and cost-effectiveness of housing projects, which are critical for affordable housing. SIAH incorporates factors related to community impact, health and wellbeing, and social equity, which are often underrepresented in other tools.

The review of the five most common building SATs, as summarized in Table 1 provides a comparison with the SIAH framework, particularly in the context of affordable housing.

As shown in Table 1, SIAH is developed with a specific focus on affordable housing, ensuring that the unique economic constraints and social needs of this sector are adequately addressed. This contrasts with more general tools like LEED or BREEAM, which may not fully consider the affordability aspect. Unlike existing tools that might lean heavily towards environmental factors, SIAH provides a balanced approach by weighing technical, economic, social, and environmental factors equally. This holistic approach is essential for the sustainability of affordable housing projects. With 127 CSFs, SIAH covers a more extensive range of factors than the five tools reviewed. Categorizations and sub-categorizations of each factor are articulated, ensuring that no aspect of sustainability is overlooked. The SIAH framework's detailed and structured approach aids stakeholders to arrive at well-informed decisions that consider long-term sustainability performance rather than short-term gains. This is particularly beneficial for affordable housing projects where cost efficiency and long-term viability are critical. Also, the framework's detailed categorization allows for flexibility and customization based on specific project needs, which is a significant advantage over more rigid tools like CASBEE or Green Star. By including a category specifically for methods and technologies, SIAH encourages the adoption of innovative construction techniques and materials, promoting advancements in housing sustainability.

Also, various studies offer diverse perspectives on sustainability assessment methodologies within the built environment context, each emphasizing different dimensions. The distinction between these studies and the current study lies in the differences present in the methodological approaches and conceptual focus emphasized during the development of their respective sustainability assessment frameworks. Atanda (2019) proposes a broad, conceptual framework for assessing social sustainability in urban contexts, offering flexibility and theoretical depth. However, the proposed framework enjoyed limited precision regarding the prioritization of indicators. Still focusing on social sustainability, Fatourehchi and Zarghami (2020) adopted a more localized approach, developing a context-specific framework for Iran's residential construction sector using a structured multi-criteria decision-making (MCDM) method. This approach enhanced the practical relevance of the emergent framework but limited its generalizability as it focused on a specific context. In their study, Ahmad and Thaheem (2018) focused on economic sustainability, presenting a quantifiable framework integrated with Building Information Modeling (BIM), which strengthened its technical applicability but suffered from an underrepresentation of social and environmental sustainability indicators. These three frameworks failed to provide for a comprehensive assessment of the three prevalent sustainability dimensions. In contrast, Olawumi et al. (2020) presented a comprehensive sustainability assessment methodology-Building Sustainability Assessment Method (BSAM) – which integrates a wide range of sustainability indicators spanning the environmental, economic, and social dimensions.

In contrast, this study presents a globally adaptable sustainability assessment methodology specifically targeted at affordable housing and incorporating an additional technical sustainability dimension. It employs a more rigorous mixed-method approach using Delphi and AHP techniques to validate 127 critical success factors and assign relative sustainability weights (RSWs) accordingly, unlike the BSAM which relied on findings from extensive literature review and expert validation (Olawumi et al. 2020). While BSAM offers a regionally relevant conceptual framework given its particular focus on developing countries situated in sub-Saharan Africa, this study demonstrates the global practical utility and appeal of the SIAH-SAT methodology by applying the emergent tool across five real-world affordable housing case studies, enabling comparative analysis through a Sustainability Index (SI). Unlike the others, the methodology being proposed by the current study aims for a balanced, multi-dimensional assessment across economic, environmental, social, and technical sustainability domains, with a strong emphasis on practical application in affordable housing contexts, thereby offering a context-sensitive yet generalizable tool for guiding sustainable urban development. Overall, SIAH-SAT provides a more comprehensive and operational framework, supporting evidence-based decision-making in diverse urban housing contexts.

3. Methodology

An exploratory mixed-method research design was utilized as the most suitable design due to the increasingly complex and interdisciplinarity level of this research as illustrated in Figure 1. Mixed-methods designs are particularly effective for conducting research on sustainability and affordable housing (Douglas et al. 2024; Moore, Strengers, and Maller

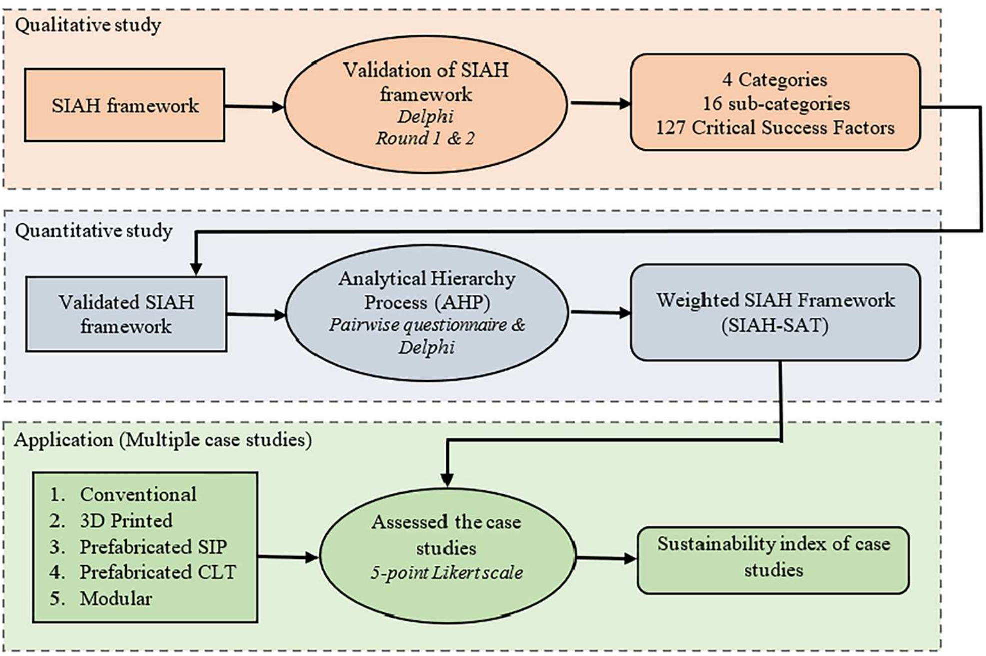

Figure 1. Research method framework.

2016; Riazi and Emami 2018), as they integrate qualitative and quantitative data to provide a comprehensive understanding of complex, multifaceted phenomena (Creswell and Plano Clark 2018). This research design supports the triangulation of expert judgments, stakeholder perspectives, and empirical data, thereby enhancing the validity and depth of analysis. In evaluating sustainability, where social, economic, technical, and environmental factors intersect, exploratory mixed-methods offer the flexibility to uncover patterns, refine constructs, and develop robust assessment tools (Creswell and Plano Clark 2018). They are especially valuable in emerging fields lacking established theories or standardized models, allowing for iterative development and validation of frameworks such as the SIAH-SAT.

In the first stage, the CSFs listed on the SIAH framework, which was previously developed through an extensive systematic literature review, bibliometric analysis, and content analysis techniques by Moghayedi et al. (2021), underwent validation by a panel of experts consisting of 27 international housing specialists. The aim was to authenticate the identified CSFs and the broader SIAH framework. To mitigate the potential influence of group dynamics and psychological factors inherent in expert focus group discussions and group decision-making the Delphi technique was employed as recommended by Belton et al. (2019).

The Delphi technique facilitates plural communication, allowing experts to efficiently share knowledge concerning complex problems. It employs a systematic and iterative process to foster consensus development, leveraging the collective expertise of a panel of specialists (Belton et al. 2019). The Delphi technique consists of the following features: (1) ensuring anonymity among the panel of experts; (2) obtaining a statistical group response through structured questioning; (3) utilizing iteration; and (4) providing controlled feedback (Pomponi et al. 2019). All these features were meticulously observed during the implementation of the Delphi method in this research.

The Delphi technique is a robust method commonly used for forecasting or investigating factors that influence decision-making (Belton et al. 2019). It has been extensively employed by scholars across various fields, including social science, management, engineering, and the built environment (Pomponi et al. 2019).

The most crucial aspect of the Delphi technique was the selection of the expert panel. The panel members of this study were chosen based on their relevant expertise and experience related to SIAH. Given the interdisciplinary nature of this study, panel members were carefully selected from various fields, cultural backgrounds, and geographical locations. Detailed information about the expert panel members is elaborated in Table 2.

Another vital consideration in the Delphi technique pertained to the number of panel members involved. Parente et al. (1984) recommended a Delphi panel size ranging from a minimum of 5 to a maximum of 50 participants to achieve accurate consensus decisions. A total of 30 experts spanning various disciplines, cultures, and locations were initially invited to participate in the study. Ultimately, 27 experts actively engaged in two rounds of the Delphi process.

In the first round of the Delphi process, a few panel members suggested adding or modifying some of the identified CSFs. However, in the second round, the panel members did not reach a consensus on any of these suggestions. Consequently, the

Table 2. Background details of panel members.

Professional background			
Engineering	Built Environment	Social science	Others
Civil [2] Structural [2] Electrical [1] Mechanical [2] Energy [1] Infrastructure [1]	Architects [3] Quantity surveyors [2] Construction manager [3] Urban planner [1]	Psychologists [1] Public health [1] Youth and Gender [1]	Technological innovator [1] Sustainable development [2]
Experience background			
<10 years	10–20 years	20–30 years	>30 years
0	8	14	5
Position role background			
Policymakers	Industry	Academic	Others
5	Designers [4] Developers [6] Housing inspectors [5]	4	NGOs [3]
Geographical Location			
Africa	Asia and Oceana	Europe	America
7	East Asia [3] Middle East [4] Oceana [2]	5	North America [2] South America [4]

SIAH framework developed by Moghayedi et al. (2021) was retained for quantitative analysis (Figure 2).

Following the validation of the CSFs and SIAH framework (see Figure 1), the AHP was employed to ascertain the relative importance weights of the SIAH categories, sub-categories, and CSFs.

AHP is a structured technique for addressing complex decision-making problems and has found extensive use in various fields of science, engineering, and the built environment (Moghayedi and Windapo 2018). AHP is a versatile and adaptable quantitative pairwise comparison method that has been frequently employed in housing research projects (Ramzanpour and Rahimi 2023). Furthermore, in studies relating to BSAS, the prevalent use of AHP as an MCDM of choice was elucidated by Lazar and Chithra (2020) in their review of relevant studies.

The AHP determines the importance of factors through the following steps:

1. Structuring the decision hierarchy, considering the goal, criteria, and sub-criteria.
2. Establishing priority among criteria and sub-criteria using pairwise comparison and developing a comparison matrix.
3. Determining the relative importance weight of criteria and sub-criteria by analyzing the corresponding eigenvectors.
4. Calculating the consistency of judgments using the Consistency Ratio (CR).

The validated SIAH framework, including its criteria, sub-criteria, and CSFs, was compared pairwise with other components at the same hierarchy level using the standard AHP scale to establish the relative importance weights. The pairwise comparison accurately determines the importance weight of each component and provides rankings at three hierarchy levels.

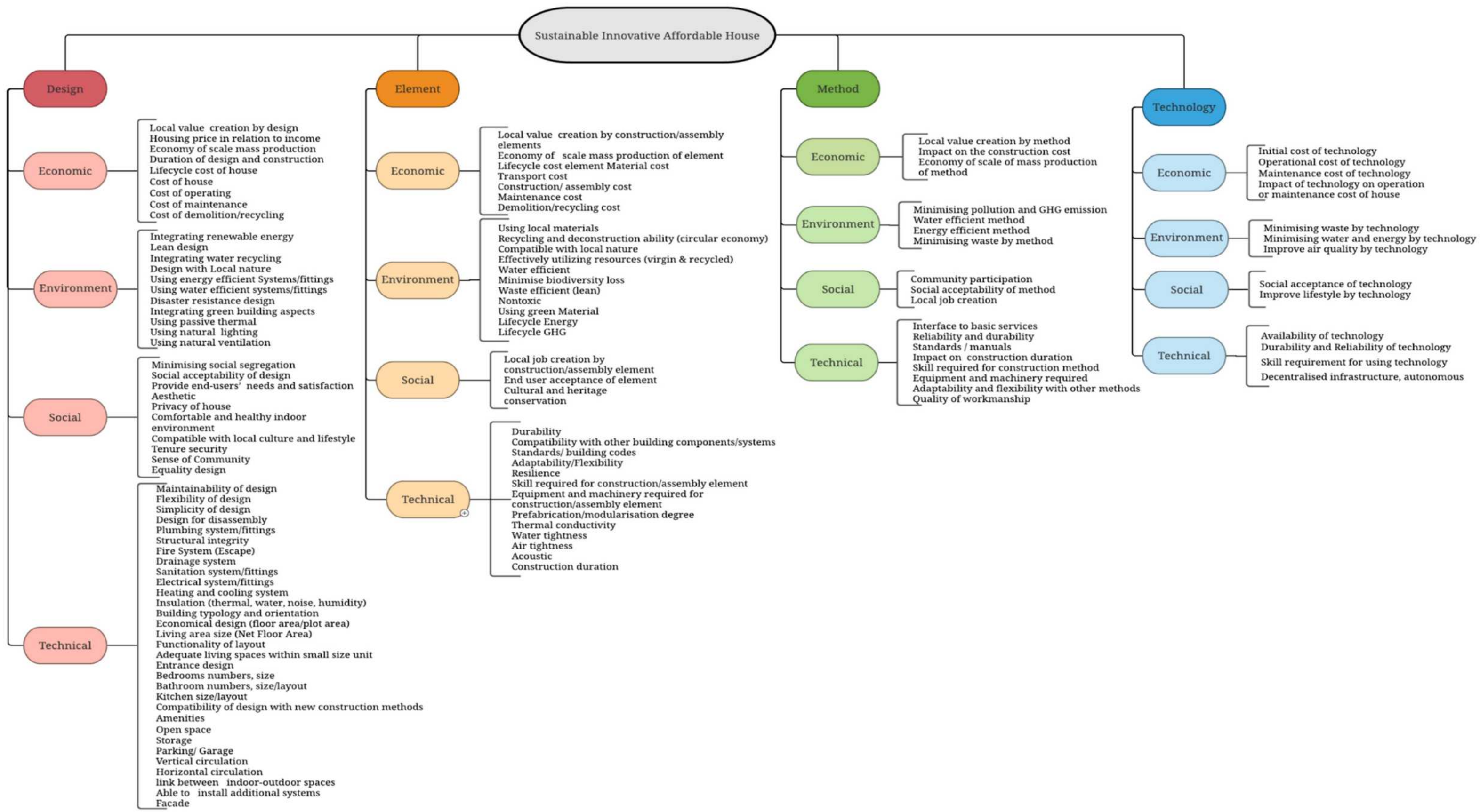

Figure 2. SIAH framework.

The consistency index (CI) and the CR of the collected data from the panel of experts were quantified using the following formulas in Expert Choice software.

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (1)$$

$$CR = \frac{CI}{RCI} \quad (2)$$

Where,

λ_{max}: eigenvalue corresponding to the matrix of pair-wise comparisons.

n: number of elements being compared.

RCI: random consistency index related to the number of criteria.

The consistency of pairwise comparisons for each member of the expert panel was measured. Consistency reveals the extent to which experts understand and capture the interactions among different criteria, sub-criteria, and CSFs of SIAH. Pairwise comparison data with a consistency ratio of less than 90% were returned to experts for correction.

To calculate the relative sustainability weights (RSWs) of each critical success factor (CSF), a multi-level weighting scheme was employed, incorporating the corresponding category and subcategory weights along with the AHP scores of each CSF, as outlined in Formula 3.

$$RSW_{CSF} = (Category_{Weight} \times Subcategory_{Weight} \times CSF_{Score}) \times 100\% \quad (3)$$

Where,

RSW_{CSF}: Relative sustainability weights of CSF.

$Category_{Weight}$: relative importance weight of category.

$Subategory_{Weight}$: relative importance weight of subcategory.

CSF_{Score}: relative score of CSF.

This RSW represents a multi-level weighting scheme structured across three hierarchical levels – categories, subcategories, and CSFs – which ensures that the final weight of each CSF reflects not only its individual AHP score but also the relative importance of its parent subcategory and overarching category. This multi-level approach offers significant advantages for evaluating the sustainability performance of affordable housing. It enhances accuracy by mirroring the hierarchical structure of housing data (e.g. individual units within developments), reduces bias by accounting for unequal selection probabilities at different levels, and increases flexibility, allowing the framework to adapt across diverse housing evaluation contexts. Moreover, it ensures a more representative analysis of diverse population characteristics, capturing variability within and between housing clusters and yielding more generalizable findings. Importantly, multi-level weighting also improves the statistical power of the evaluation by increasing the efficiency of estimates and reducing standard errors, resulting in more precise, reliable, and comprehensive assessments of sustainability outcomes.

Ultimately, the RSW of each CSF, derived from Formula 3, serves as its respective importance weight. This weight is then multiplied by the assessed level of provision for that CSF, which can be evaluated by various housing stakeholders using either a

Likert scale or a continuous scale. The summation of these weighted scores across all CSFs determines the overall SI of a housing case, as presented in Formula 4.

$$SI = \sum (RSW_{CSFn} \times Level\ of\ \ Provision_{CSFn}) \tag{4}$$

Where,

RSW_{CSFn}: Relative sustainability weights of CSF.

$Level\ of\ \ Provision_{CSFn}$: Level of provision of CSF.

To validate the capability of the SIAH-SAT in evaluating the SI across different housing types, five distinct affordable housing cases were carefully selected. A panel of eight experts assessed the level of provision for each case using the 127 SIAH CSFs, focusing on aspects such as design, components, construction methods, and applied technologies. The evaluation was conducted using a five-point Likert scale, informed by comprehensive documentation provided to the panel, including technical and performance specifications for each case, as well as survey responses and feedback from end-users.

4. Results

As highlighted previously, the AHP method was used to assess the RSWs of four categories, sixteen sub-categories, and 127 CSFs within the SIAH framework. Each expert provided individual pairwise scores, from which initial RSWs were derived. The results of the AHP analysis were subsequently discussed with the expert panelists. Necessary minor adjustments were made to the initial weights, and the final RSWs were agreed upon by all panelists. The RSWs of SIAH categories and sub-categories as high-level result of AHP analysis presented in Figure 3.

As shown in Figure 3, the housing design category holds the highest RSW at 47.9%, indicating that the design phase has the most significant impact on housing sustainability. This underscores the importance of integrating sustainability principles early in the design process, aligning with findings from previous studies (Adabre et al. 2020). The subcategories of housing design are weighted as follows: social (39.2%), environmental (29.1%), technical (22.2%), and economic (9.4%). The strong emphasis on social sustainability highlights the importance of designs that promote health and well-being, while the environmental focus emphasizes the need to address environmental protection and climate change. The technical subcategory is also weighted highly due to the need to meet building standards and regulations, with economic considerations receiving the least weight.

The housing element category, with an RSW of 21.7%, ranks second in importance. This category covers core housing components and materials, reflecting the influence of these elements on sustainability. Social, environmental, and technical subcategories are equally weighted at 28.6%, with economic sustainability receiving 14.3%, illustrating a balanced approach that values both social and environmental sustainability. Previous research (Moghayedi, Phiri, and Ellmann 2023; Ramzanpour and Rahimi 2023; Winston 2022) has similarly emphasized the importance of innovative housing elements and materials for sustainability, although economic factors, while still significant, receive less emphasis.

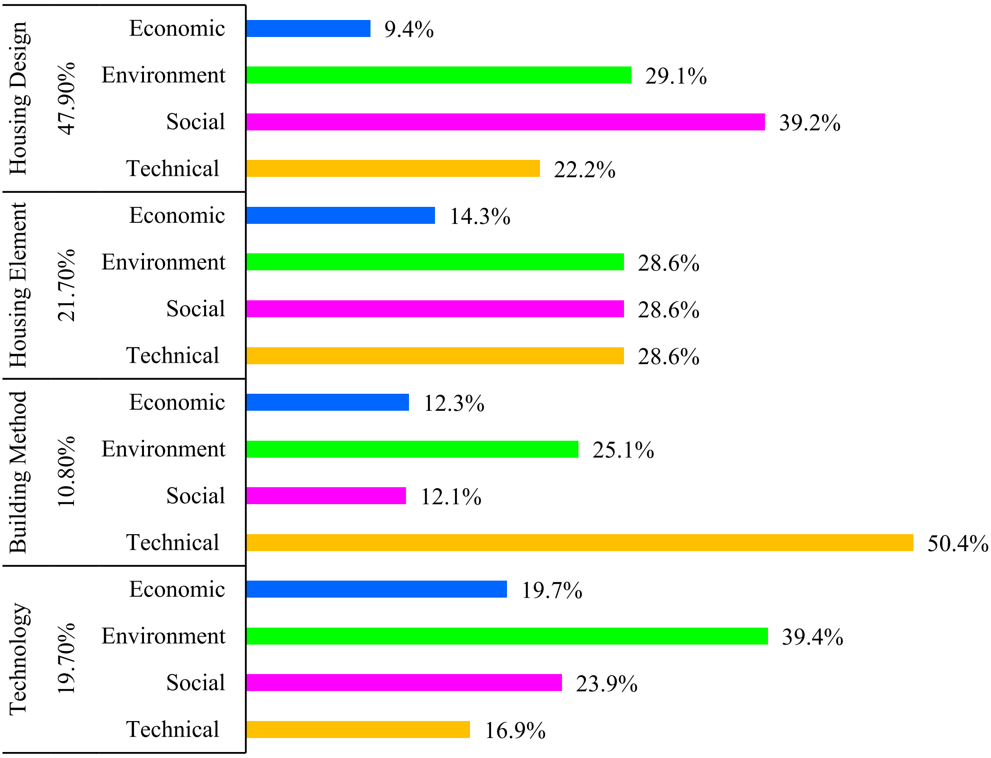

Figure 3. Relative sustainability weights (RSWs) of SIAH categories and their sub-categories.

The technology category, ranked third with a 19.7% RSW, focuses on integrating technological innovations in housing. Environmental benefits are prioritized with a 39.4% RSW, followed by social (23.9%), economic (19.7%), and technical (16.9%) subcategories. This shows that technology is valued for its environmental contributions, while social benefits, such as improving quality of life, are also important. Previous studies (Dok-Yen, Duah, and Addy 2023; Moghayedi, Phiri, and Ellmann 2023) have highlighted the role of technology in enhancing both environmental and social sustainability.

Finally, the building method category, with a 10.8% RSW, is the least weighted, indicating that while construction methods matter, they are not as critical to housing sustainability as design and elements. The technical subcategory (50.4%) dominates, reflecting the importance of technical efficiency in innovative construction methods. This aligns with the trend toward modern construction methods noted in studies by Bhyan, Shrivastava, and Kumar (2023). The environmental subcategory (25.1%) also has a significant weight, highlighting the need to ensure that building methods are environmentally responsible, while economic (12.3%) and social (12.1%) aspects receive lower emphasis.

4.1. Relative sustainability weights of SIAH CSFs

A pairwise comparison of CSFs for each category was conducted using a standard AHP questionnaire. This method facilitated the calculation of the relevant scores for each CSF. Subsequently, the RSW of each CSF was determined by multiplying the relative score of the CSF by the RSW of the relevant subcategory and category. The resulting RSWs for the CSFs across the four SIAH categories are presented in Tables A1, A2, A3 and A4, respectively.

4.1.1. Design CSFs

As indicated in Table A1, it is evident that the design category stands out as the most important in housing sustainability. This is not only due to its highest RSW but also because it encompasses many CSFs (61) and includes many of the most important CSFs in this category. 6 out of the top ten SIAH CSFs are in this category. The highest RSW (4.83%) belongs to 'Tenure security' (DS8) a social CSF of housing design, which ensures long-term residency stability. 'Privacy of house' (DS5), another social CSF of design, ranks third, highlighting its critical importance for occupant comfort and satisfaction.

'Disaster resistance design' (DEN7) is another high-impact CSF, ranked fifth, under the environmental sub-category of housing design, essential for resilience against both natural and human-made disasters. The sixth, ninth, and tenth highest CSFs are also under the design category: 'Provide end-users' needs and satisfaction' (DS3), 'Comfortable and healthy indoor environment' (DS6), and 'Design with local nature' (DEN4). These three CSFs are critical for user-centric design, health and well-being of residents, and ensuring harmony with local ecosystems. Furthermore, 25 CSFs of housing design are ranked among the top 50 most important CSFs, and 21 CSFs fall between the 50–100 rankings, underlining the comprehensive impact and significance of the design category in sustainable housing.

4.1.2. Element CSFs

The housing element category significantly contributes to housing sustainability, both in terms of its RSW of 21.7% and the number of CSFs it encompasses, totaling 35. Several high-weighted CSFs within this category, as listed in Table A2, highlight its importance.

Two social CSFs 'End user acceptance of element' (ES2) and 'Cultural and heritage conservation' (ES3) are both ranked as the 7th most important CSFs within the SIAH framework, underscoring the significance of building element category. High End User acceptance indicates that housing elements meet users' needs and preferences, resulting in higher satisfaction and long-term sustainability. The (ES2) CSF ensures that housing developments are user-centric, enhancing overall satisfaction and promoting continued use and maintenance of the housing elements. ES3 emphasizes the importance of preserving cultural and heritage aspects within housing elements. By respecting and integrating local cultural values, housing developments promote social sustainability and community cohesion. This not only maintains cultural continuity but also enhances the unique identity of the housing projects, making them more appealing and acceptable to the local population.

The high ranking of these two social CSFs within the housing element category highlights the importance of end-user satisfaction and cultural preservation, both critical for achieving long-term sustainability and acceptance of housing projects. Additionally, 8 CSFs within the Housing Element category are ranked among the top 50 most important CSFs, while 20 CSFs fall between the 50–100 rankings. This underscores the high impact and significance of the innovative housing elements and materials category in sustainable housing, which primarily addresses the sustainability of innovation in housing elements and materials.

4.1.3. Methods CSFs

The methods category, with an RSW of 10.8%, is an important component of housing sustainability, encompassing 18 CSFs. As shown in Table A3, 'Standards / manuals' (MT3) is a technical CSF of the building method with the highest RSW (rank 18). MT3 underscores the need for adherence to established standards and guidelines to ensure quality and consistency. 8 CSFs within the building method category are ranked among the top 50 most important CSFs, and 6 CSFs fall between the 50–100 rankings, mainly under the technical and environment sub-categories. This highlights the significance of addressing both the technical and environmental aspects of innovative building methods to enhance overall sustainability.

4.1.4. Technology CSFs

The technology category, comprising 19.7% of the overall sustainability weight, plays a pivotal role in housing sustainability with its 13 CSFs as listed in Table A4. 'Minimising Water and Energy by Technology' (TEN2) ranked 2nd among all SIAH CSFs, in the environment subcategory underscores the critical importance of integrating technologies that reduce water and energy consumption. This factor highlights the necessity of sustainable practices in housing, promoting the efficient use of resources while significantly reducing environmental impact. Implementing such technologies not only conserves valuable resources but also lowers operating costs, thereby enhancing both the sustainability and cost-effectiveness of housing projects. By prioritizing water and energy efficiency, housing developments can achieve greater environmental stewardship and economic savings, benefiting both the planet and the residents. 'Improve Lifestyle by Technology' (TS2) ranked 4th among all CSFs, in the social subcategory emphasizes the pivotal role of technology in enhancing the quality of life for residents. This CSF includes technologies like smart home systems, advanced healthcare features, and modern entertainment options, all of which contribute to creating a more comfortable and convenient living environment. High social acceptance and satisfaction are essential for the long-term viability and widespread adoption of these technologies. Ensuring that housing developments incorporate technologies that meet the evolving needs and preferences of residents fosters a sense of well-being and satisfaction, thereby supporting the sustainability and success of the housing projects.

Referring to the Tables A1-A4, it is evident that in the realm of affordable housing sustainability, the top 10 CSFs are identified as follows:

1. Tenure security (DS8)
2. Minimizing water and energy through technology (TEN2)
3. Privacy of the house (DS5)
4. Improvement of lifestyle through technology (TS2)
5. Disaster resistance design (DEN7)
6. Provision of end-users' needs and satisfaction (DS3)
7. End-user acceptance of elements (ES2)
8. Cultural and heritage conservation (ES3)

9. Achievement of a comfortable and healthy indoor environment (DS6)
10. Design integration with the local natural environment (DEN4)

CSFs such as tenure security, privacy, end-user acceptance, cultural and heritage conservation, and lifestyle improvement emphasize the importance of meeting residents' needs and preferences. These factors ensure housing developments are well-received by the community, fostering social cohesion and long-term sustainability. The critical role of these social factors in housing and household sustainability have been underscored by several studies as well (Adabre and Chan, 2019; Bhyan, Shrivastava, and Kumar 2023; Lazar and Chithra 2020).

Furthermore, efforts to minimize water and energy use through technology and disaster resistance design underscore the necessity of cost-effective and resilient housing solutions. These strategies lower operational and maintenance costs, enhancing affordability and sustainability performance over time (Moghayedi, Phiri, and Ellmann 2023).

As emphasized by the European Environment Agency (2024) and the World Green Building Council (2024), technologies and designs that reduce resource consumption and engender harmony with the natural environment play a crucial role in diminishing the environmental impact of housing projects. They ensure developments are environmentally sensitive, promoting biodiversity and conserving resources. The emphasis on user-centric designs and creating comfortable, healthy indoor environments highlights the significance of technical excellence in housing. These factors ensure that developments are not only functional and durable but also support the health and well-being of residents, as demonstrated by the modeling and simulation in SIAH-Livable (Moghayedi, Phiri, and Ellmann 2023).

These top 10 CSFs, primarily derived from design categories (6 CSFs) and elements of technology (2 CSFs each), collectively contribute to a balanced consideration of social, economic, environmental, and technical aspects in ensuring the sustainability of housing.

4.2. Validating the SIAH sustainability assessment tool

To validate the credibility and compatibility of the SIAH-SAT, evaluations were conducted across five cases. The SIAH-SAT was applied to five distinct cases, each highlighting unique technical designs, building elements, materials, construction methods, and technologies.

The five cases explore a range of low-cost housing systems: Case 1 examines conventional housing in the Global South using bricks, mortar, and traditional methods. Case 2 features a low-cost 3D-printed house with hollow recycled concrete mortar. Case 3 focuses on a prefabricated monolithic structure with net-zero energy performance. Case 4 investigates a prefabricated cross-laminated timber house targeting net-zero carbon emissions. Case 5 presents a modular unit made from recycled reinforced light concrete, incorporating advanced water and energy-efficient technologies, with an emphasis on disassembly and recycling.

The specifications and detailed information of the chosen five cases are summarized in Table 3.

These cases showcase a spectrum of innovative construction techniques and materials aimed at improving housing efficiency and resilience. By including both conventional

Table 3. Cases technical details and specifications.

Specification		Case study 1	Case study 2	Case study 3	Case study 4	Case study 5
Size		50m2	44m2	50m2	52 m2	48 m2
Design		Conventional	Lean, Inclusive, design for disassembly or recycling	Lean, Disaster resistance, Energy and water efficient, Passive, Inclusive, design for disassembly or recycling, Net-Zero Energy	Lean, Disaster resistance, Energy and water efficient, Passive, Inclusive, design for disassembly or recycling, Net-Zero Carbon	Lean, Energy and water efficient, Inclusive, design for disassembly or recycling
Building Elements & Materials	Foundation	Surface beds with thickened edge beams (raft foundation)				
	Walling systems	Load bearing bricks and mortar	Hollow Recycled Concrete Mortar	Structural Insulated Panel (SIP), Mineral wool insulation, encapsulated by Zinc-Aluminium sheets with an AZ150 Coating	Seven layers Cross Laminated timbers	Recycled Reinforced light concrete
	Roofing	Timber roof truss coverings with clay brick and insulated ceilings	Timber roof truss coverings with steel sheet and insulated ceilings			
Construction Method		Conventional	3D printing	Prefabricated	Prefabricated	Modular
Technology		Basic	Basic	Decentralized systems, Water & Energy efficient	Decentralized systems, Water & Energy efficient	Water & Energy efficient

and cutting-edge technologies, the validation process aims to demonstrate the robustness and versatility of SIAH-SAT in assessing the sustainability of various housing types.

A panel comprising of eight experts assessed the level of provision for each of the 127 CSFs of SIAH, using a 5-point Likert Scale. To support this evaluation, comprehensive information including design details, technical specifications, and resident feedback was provided to the expert panel to facilitate accurate and informed assessments. The primary objective of obtaining the RSW and level of provision for each CSF was to calculate the SI of affordable housing using Formula 4. Ultimately, these indicators yielded the SI of each individual case, as shown in Table A5.

The heat map uses a color scale to facilitate quick identification of hotspots for different CSFs within each case: red (<33%) indicates not sustainable, orange (33%–66%) indicates low sustainability, and green (>66%) indicates sustainability for the specific CSFs.

The results of the analysis of the cases' sustainability performance, as presented in Table A5, demonstrate the capability of the SIAH-SAT to accurately quantify the sustainability performance of various housing types, regardless of their design, building elements and materials, construction methods, and technologies used throughout the design, construction, and operational stages. To illustrate the capabilities of the SIAH-SAT, the SI of five cases was elaborated in detail. These cases were then compared in terms of four main categories and their sub-categories. This comparison highlights the strengths and weaknesses of each housing type across various sustainability dimensions, providing a comprehensive evaluation of their sustainability performance.

4.2.1. Sustainability index of conventional house (Case 1)

Case 1 as conventional housing achieved a SI of 55.62%, falling short of the SIAH benchmark in all categories as illustrated in Figure 4.

In the design category, Case 1 scored an RSW of 25 against the SIAH benchmark of 48, yielding a design SI of 52%. This indicates low sustainability performance due to a lack of sustainable design techniques such as passive, lean, inclusive, or resilient features and insufficient social design elements, like community-building or reducing social segregation, which aligns with Adabre et al. (2020) on the need for sustainability principles in early design stages.

For the elements category, an RSW of 14 against the benchmark of 22 results in a moderate SI of 64%, reflecting mixed quality among elements. This finding resonates with Moghayedi, Phiri, and Ellmann (2023), who discuss the sustainability challenges tied to material variability.

In the methods category, an RSW of 6 against 11 yields an SI of 55%, indicating reliance on less sustainable methods like traditional brick and mortar, which aligns with Bhyan, Shrivastava, and Kumar (2023) on the limitations of conventional construction approaches.

Lastly, in the technology category, an RSW of 10 versus a benchmark of 20 results in an SI of 50%, due to minimal technology integration, consistent with Dok-Yen, Duah, and Addy (2023), who emphasize the role of technological advancements in improving housing sustainability. Overall, Case 1 reveals low sustainability across all categories, with notable gaps in design and technology, aligning with the World Green Building Council's (2024) advocacy for holistic, sustainable housing practices.

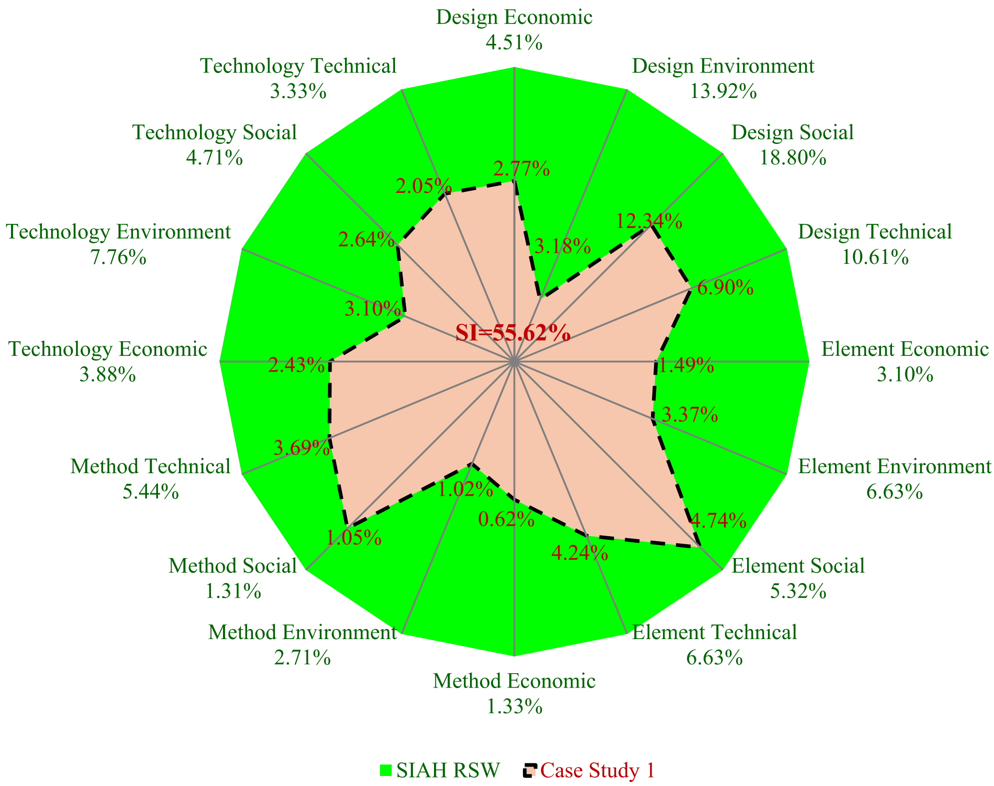

Figure 4. Sustainability of case 1 compared to SIAH.

4.2.2. Sustainability index of 3D-printed house (Case 2)

When compared to the SIAH RSW thresholds, the sustainability performance of Case 2, which employs 3D-printing technology for housing construction, highlights a moderate SI of 68.38% as shown in Figure 5.

In the design category, Case 2 achieved an RSW of 34, compared to the SIAH RSW threshold of 48, resulting in a design SI of about 71%. This strong performance is primarily due to the flexibility and design freedom offered by 3D-printing technology. However, social aspects are less emphasized, with limited focus on fostering community or reducing social segregation, aligning with findings by Moghayedi et al. (2024) on the challenges of integrating social design in innovative housing.

In the elements category, an RSW of 14 against the SIAH RSW of 22 yields a moderate SI of 64%, reflecting limitations in material sustainability. This is mainly due to the reliance on cementitious materials, which are costly and have a notable environmental impact, a concern noted by Winston (2022) regarding the sustainability of high-carbon materials. The method category has an RSW of 7, compared to the SIAH RSW of 11, giving it a moderate SI of 64%. This is due to the specialized machinery and skills required, which limit local job creation and raise costs due to the technology's relative infancy, consistent with Bhyan, Shrivastava, and Kumar (2023), who highlight barriers in scaling 3D-printing for local economies.

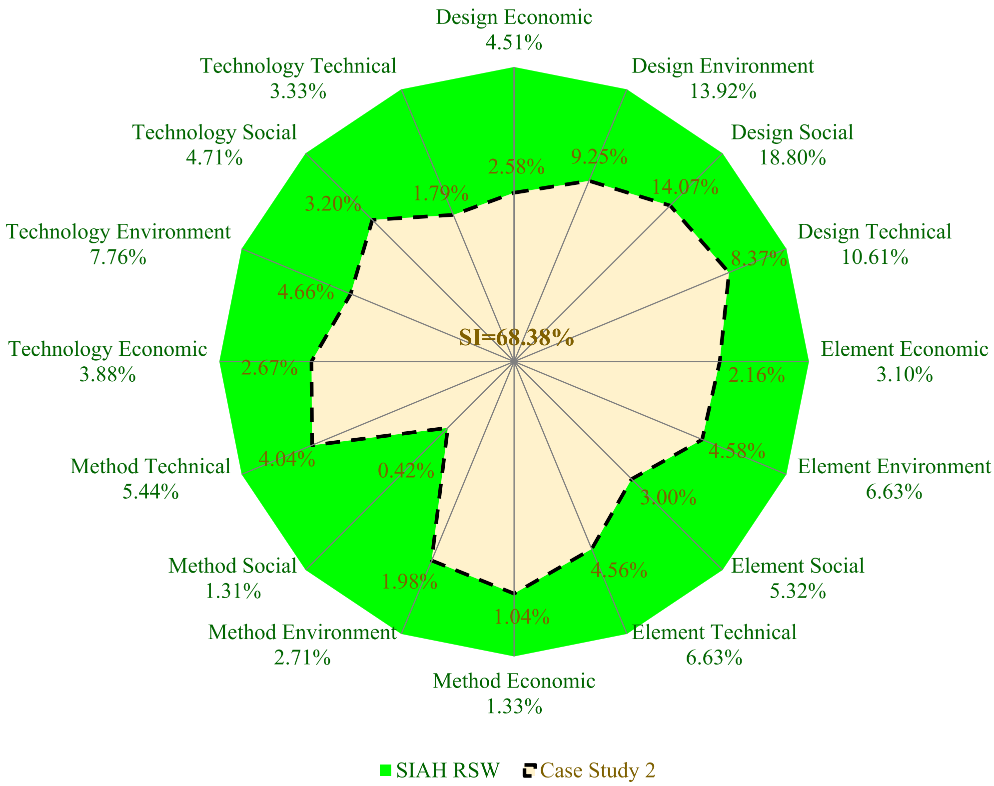

Figure 5. Sustainability of case 2 compared to SIAH.

In the technology category, Case 2 has an RSW of 12 compared to the SIAH RSW of 20, achieving an SI of 60%. This lower score reflects a lack of efficient heating and cooling systems, which could otherwise enhance energy efficiency, as echoed by Dok-Yen, Duah, and Addy (2023), who advocate for integrating energy-efficient technologies in sustainable housing. Overall, while Case 2 shows moderate sustainability across categories, key gaps highlight areas for improvement, aligning with the WGBC's (2024) emphasis on the importance of closing technology gaps in sustainable housing.

4.2.3. Sustainability index of net-zero energy house (Case 3)

The sustainability of Case 3, a prefabricated Net-Zero energy house, compared to the SIAH RSW thresholds, reveals a significant SI of 85.42% as shown in Figure 6.

In the design category, Case 3 achieved an RSW of 43, compared to the SIAH threshold of 48, resulting in a high SI of 90%. This strong performance stems from integrating various sustainable design techniques, including energy efficiency, passive design, design for disassembly or recycling, and achieving net-zero energy. These align closely with the SIAH model, supporting evidence from literature that emphasizes the effectiveness of net-zero design strategies for sustainable housing (Moghayedi et al. 2024).

For the elements category, Case 3 reached an RSW of 18 against a threshold of 22, yielding a high SI of 82%. This score reflects the sustainable nature of the materials

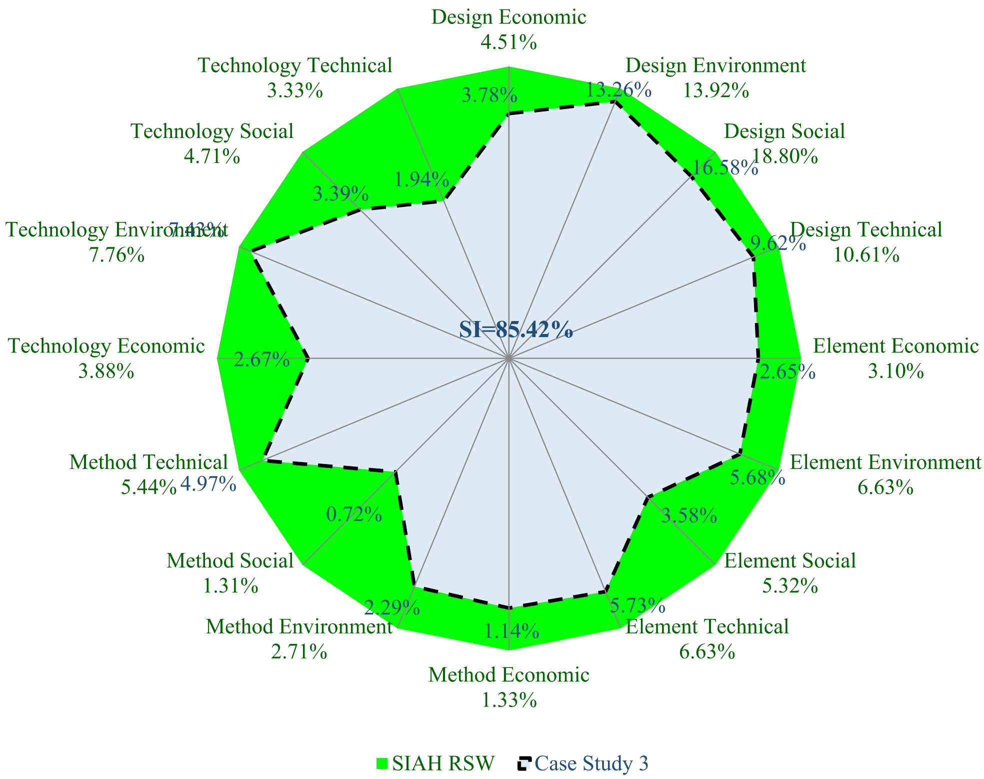

Figure 6. Sustainability of case 3 compared to SIAH.

and innovative components used, indicating alignment with research on the sustainability benefits of advanced material use in housing projects (IEA, 2021).

In the method category, Case 3 scored an RSW of 9, compared to the SIAH RSW of 11, leading to a high SI of 82%. This rating highlights the sustainability of prefabricated monolithic SIP panels, which require minimal labor skills, promote local employment, and enable rapid, high-quality construction. Such findings align with studies that advocate for prefabrication and modular approaches to enhance construction sustainability and social benefits (Moghayedi and Awuzie 2023).

Lastly, in the technology category, Case 3 achieved an RSW of 15 against a target of 20, resulting in a solid SI of 75%. The use of decentralized renewable energy sources and efficient lighting and water heating systems contribute to this score, echoing literature on the benefits of incorporating renewable technologies to improve energy efficiency in residential construction (Moghayedi et al. 2024). Overall, Case 3 demonstrates strong sustainability performance across all categories, aligning with recognized sustainable practices in housing design, material innovation, prefabrication, and renewable energy use, though slight adjustments could help it fully achieve SIAH benchmarks.

4.2.4. Sustainability index of net-zero carbon house (Case 4)

The sustainability of Case 4, a Net-Zero carbon house, compared to the SIAH RSW thresholds reveals a high SI of 83.30% as shown in Figure 7.

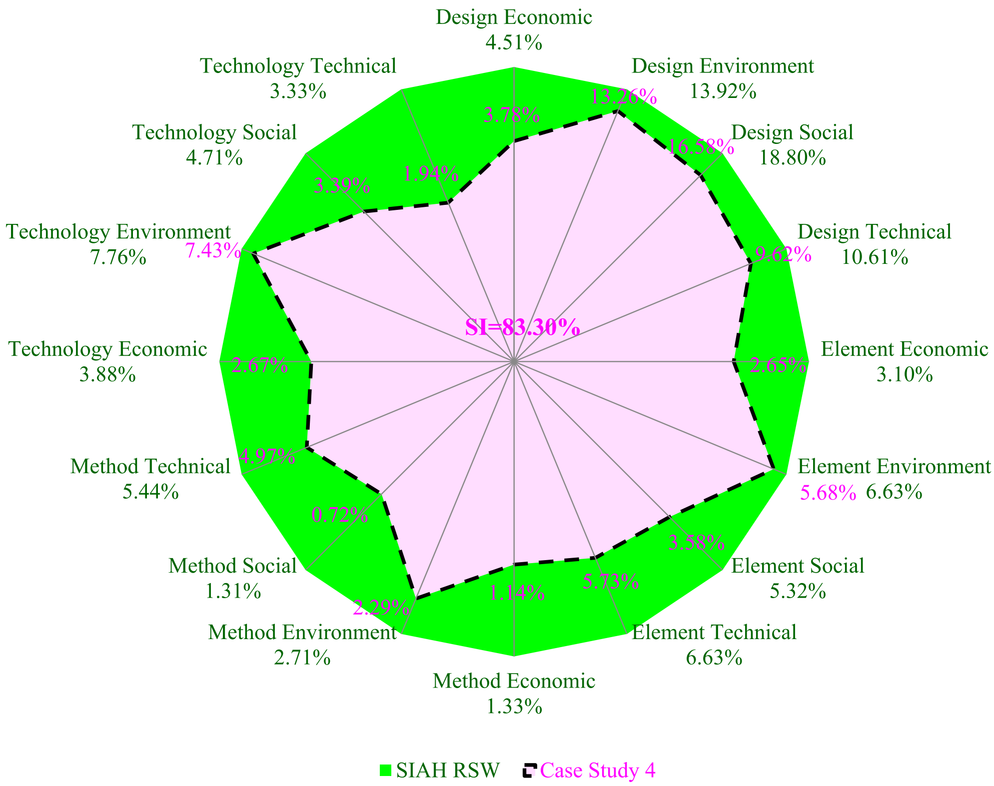

Figure 7. Sustainability of case 4 compared to SIAH.

In the design category, Case 4 achieved an RSW of 42 compared to the SIAH threshold of 48, resulting in a high SI of approximately 88%. This strong design sustainability is due to the application of sustainable design techniques such as lean construction, disaster resistance, passive design, and energy and water efficiency aimed at net-zero carbon. These strategies align closely with established literature highlighting the role of integrated, resilient design in sustainable construction (Galster & Lee, 202).

For the element category, Case 4 reached an RSW of 17 against a benchmark of 22, yielding a good SI of around 77%. This score reflects the environmental benefits of using natural materials, though the high cost of CLT somewhat limits sustainability in this area. This finding is consistent with research indicating that, despite higher initial costs, natural materials provide significant long-term environmental value in sustainable housing (Larsen et al. 2022).

In the method category, an RSW of 8 compared to a SIAH threshold of 11 results in a SI of approximately 73%, signifying reasonable sustainability with the prefabricated CLT method. The assembly of CLT requires minimal labor skills, promotes local employment, and allows for rapid, high-quality construction (Moghayedi and Awuzie 2023).

For the technology category, Case 4 achieved an RSW of 15 out of a possible 20, translating to a SI of 75%. This rating is largely due to the decentralized systems implemented, such as renewable energy sources and solar gazers, which support net-zero carbon goals

(IEA, 2021). Overall, Case 4 demonstrates high sustainability performance across categories, with prefabricated CLT, passive design, and decentralized systems proving effective in achieving net-zero carbon.

4.2.5. Sustainability index of modular house (Case 5)

The SI of Case 5, which employs a modular construction approach, achieved a score of 71.74% as illustrated in Figure 8.

In the design category, Case 5 achieved an RSW of 36 against the SIAH threshold of 48, indicating a good SI of 75%. This performance is largely attributed to the design for manufacturing (DfM) approach used, which optimizes construction efficiency and reduces waste (Adabre et al. 2020).

For the element category, Case 5 scored an RSW of 15 out of 22, resulting in a moderate SI of 68%. This score reflects the lower environmental sustainability associated with cementitious materials, compounded by high costs of modular elements and transportation, which aligns with study of Moghayedi and Awuzie (2023).

In the method category, an RSW of 8 compared to the SIAH threshold of 11 yields a SI of approximately 73%, reflecting the benefits of modular methods in achieving high construction speed and quality. However, the specialized machinery and skills required do not significantly contribute to local employment, highlighting lower social sustainability (Winston 2022).

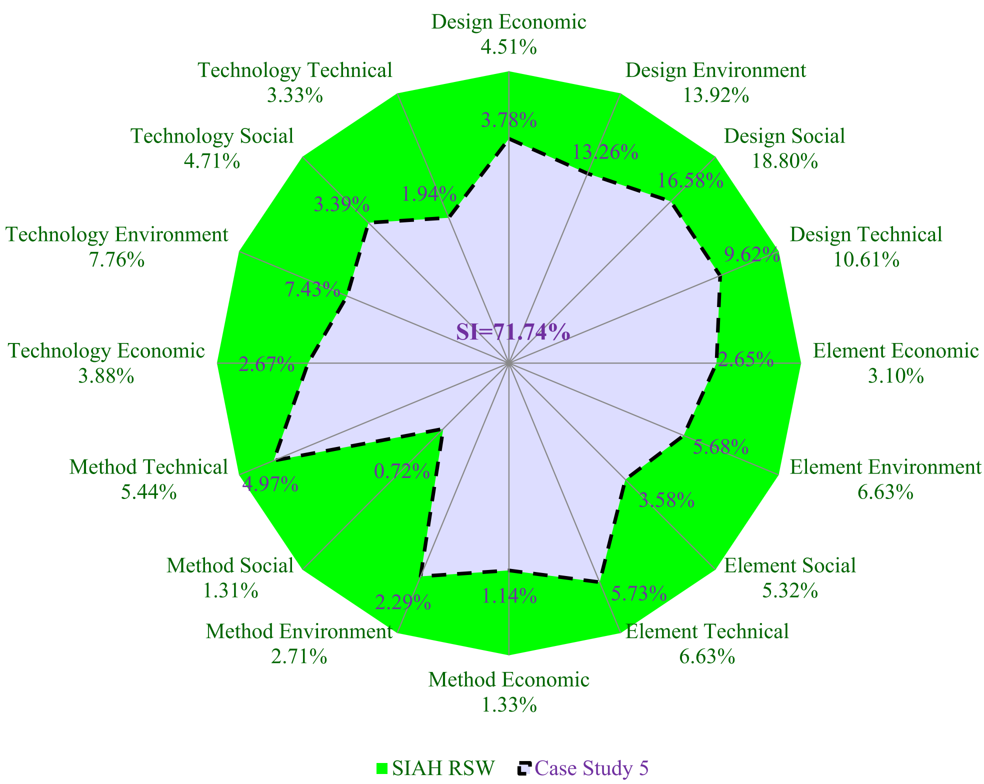

Figure 8. Sustainability of case 5 compared to SIAH.

For technology, Case 5 attained an RSW of 12 against a SIAH benchmark of 20, yielding a moderate SI of 60%. This score stems from limited integration of sustainable technologies, such as efficient water heating and lighting systems, which, as noted in recent studies, are critical for achieving higher environmental performance in housing (Moghayedi et al. 2024). Overall, Case 5 exhibits an acceptable level of sustainability, indicating that modular construction is an effective approach for sustainable housing. However, targeted improvements, particularly in material sustainability and technology integration, are necessary to fully meet SIAH benchmarks and optimize sustainability outcomes, as emphasized by several sustainable housing research (WGBC 2024).

5. Implications of the study's findings

5.1. Practical implications

Three key aspects of implications could be argued here. Firstly, in terms of the practical implications SIAH-SAT offers significant advancement in sustainable housing assessment by providing a comprehensive, housing-specific tool capable of evaluating economic, social, environmental, and technical dimensions addressing key gaps in existing SATs. Uniquely tailored for affordable housing, it enables stakeholders such as policymakers, developers, architects, and planners to integrate sustainability from early design through construction and operation. The findings highlight the superior sustainability performance of prefabricated housing, particularly those using MMCs and sustainable materials. This supports a shift toward innovative building practices that enhance speed, quality, and sustainability when selected through systematic evaluation. The SIAH-SAT tool also helps with identifying specific sustainability-related shortfalls in housing projects, offering a clear roadmap for improving design strategies, material choices, and technology integration. Its holistic approach ensures a more accurate and balanced sustainability evaluation, supporting the development of truly sustainable and inclusive housing solutions. Secondly, in terms of the policy implications decision makers can leverage insights from the SIAH-SAT to formulate targeted policies that promote sustainable and affordable housing. By recognizing the value of innovative designs, materials, and technologies, policies can be designed to incentivize the adoption of sustainable practices, particularly in contexts facing housing shortages and affordability challenges, such as those in the Global South. And finally, the research implications allow laying the groundwork for future research on sustainable housing innovations. The SIAH framework offers a foundation for investigating new materials, construction techniques, and technologies, encouraging ongoing advancement in sustainable housing practices and evaluation methods.

6. Conclusions and limitations

This study developed and validated the SIAH-SAT, a dynamic sustainability assessment tool tailored for affordable housing, to contribute to the global discourse on housing sustainability. Utilizing 127 CSFs, the study conducted an AHP analysis with input from a diverse global expert panel to determine RSWs across four categories, 16 subcategories, and 127 CSFs. This resulted in the SIAH-SAT tool.

The tool's capability was validated through its application in the evaluation of five distinct housing cases – conventional, 3D-printed, prefabricated net-zero energy, prefabricated CLT net-zero carbon, and modular housing. The results confirmed SIAH-SAT's effectiveness in assessing sustainability across diverse housing types by analyzing design, construction elements, methods, and innovative technologies. Prefabricated approaches, particularly those employing SIPs and CLT, achieved the highest sustainability indices, emphasizing the benefits of integrating passive design, lean construction, and renewable technologies. Conversely, conventional and 3D-printed houses scored lower, highlighting limitations in design innovation and technological integration. The modular case showed moderate performance, pointing to both its potential and areas for improvement, such as cost management.

The SIAH-SAT demonstrated capability as a robust, multi-dimensional tool which is appropriate for evaluating sustainability performance across economic, environmental, social, and technical dimensions throughout all housing development stages. Its detailed structure spanning categories and subcategories enabled stakeholders to identify high-performing systems and areas needing enhancement. By equipping planners, policy-makers, developers, and communities with actionable insights, the SIAH-SAT supports informed decision-making, promoting more sustainable, inclusive, and resilient housing development globally.

6.1. Limitations

While the SIAH-SAT offers a comprehensive assessment of housing sustainability performance, it is limited to evaluating the house itself, excluding broader contextual factors such as neighborhood environment, access to amenities, and urban infrastructure. This limits its ability to capture site-specific sustainability factors, particularly relevant in low-income neighborhoods of the Global South. Future research should expand the framework to include neighborhood-level assessments for a more holistic view of sustainability. The study also relies heavily on expert evaluations based on technical specifications and resident feedback. While the use of a diverse expert panel aimed to reduce bias, subjectivity remains a potential limitation. Future studies should incorporate more quantitative data and explore advanced data collection methods, such as remote sensing and big data analytics, to enhance the reliability and objectivity of sustainability assessments.

Moreover, longitudinal studies tracking the performance of sustainable housing overtime would provide critical insights into the long-term effectiveness of various design and construction strategies. Such studies would help validate, refine, and further strengthen the SIAH-SAT's relevance and application in sustainable housing development.

Disclosure statement

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Appendix

Category	Subcategory	Label	RSW	Case 1	Case 2	Case 3	Case 4	Case 5
Design (47.9%)	Economic 9.4%	DEC1	0.23%	0.09%	0.14%	0.18%	0.23%	0.14%
		DEC2	1.36%	1.36%	0.27%	1.09%	0.82%	0.82%
		DEC3	0.18%	0.04%	0.18%	0.14%	0.11%	0.18%
		DEC4	0.47%	0.09%	0.47%	0.38%	0.38%	0.38%
		DEC5	0.91%	0.36%	0.55%	0.73%	0.73%	0.73%
		DEC6	0.46%	0.37%	0.28%	0.46%	0.46%	0.37%
		DEC7	0.40%	0.16%	0.24%	0.40%	0.32%	0.40%
		DEC8	0.32%	0.25%	0.32%	0.25%	0.19%	0.32%
		DEC9	0.19%	0.04%	0.15%	0.15%	0.15%	0.15%
	Environment 29.10%	DEN1	0.63%	0.13%	0.38%	0.63%	0.63%	0.50%
		DEN2	0.33%	0.07%	0.33%	0.33%	0.27%	0.33%
		DEN3	0.86%	0.17%	0.69%	0.86%	0.86%	0.69%
		DEN4	1.95%	0.78%	1.17%	1.95%	1.95%	1.17%
		DEN5	1.21%	0.24%	0.73%	1.21%	1.21%	0.97%
		DEN6	1.21%	0.24%	0.73%	1.21%	1.21%	0.97%
		DEN7	2.59%	0.52%	1.56%	2.07%	1.56%	2.07%
		DEN8	0.72%	0.14%	0.43%	0.58%	0.72%	0.43%
		DEN9	1.46%	0.29%	0.88%	1.46%	1.46%	0.88%
		DEN10	1.48%	0.30%	1.18%	1.48%	1.48%	0.89%
		DEN11	1.46%	0.29%	1.17%	1.46%	1.46%	0.88%
	Social 39.20%	DS1	0.98%	0.59%	0.59%	0.78%	0.98%	0.59%
		DS2	0.98%	0.59%	0.78%	0.98%	0.98%	0.59%
		DS3	2.42%	0.97%	1.45%	1.94%	1.94%	1.45%
		DS4	0.53%	0.21%	0.21%	0.42%	0.42%	0.32%
		DS5	2.99%	2.39%	2.99%	2.99%	2.99%	2.99%
		DS6	2.07%	0.83%	1.24%	2.07%	2.07%	1.65%
		DS7	1.30%	0.78%	0.78%	1.04%	1.30%	0.78%
		DS8	4.83%	4.83%	4.83%	3.86%	3.86%	4.83%
		DS9	1.05%	0.84%	0.21%	0.84%	0.63%	0.21%
		DS10	1.67%	0.33%	1.00%	1.67%	1.67%	1.34%
	Technical 22.20%	DT1	0.39%	0.16%	0.31%	0.31%	0.31%	0.31%
		DT2	0.28%	0.17%	0.28%	0.28%	0.28%	0.22%
		DT3	0.13%	0.10%	0.10%	0.08%	0.08%	0.05%
		DT4	0.19%	0.08%	0.19%	0.19%	0.19%	0.19%
		DT5	0.12%	0.02%	0.07%	0.12%	0.09%	0.07%
		DT6	0.35%	0.21%	0.28%	0.35%	0.35%	0.28%
		DT7	0.95%	0.76%	0.95%	0.95%	0.76%	0.95%
		DT8	0.49%	0.20%	0.39%	0.39%	0.39%	0.39%
		DT9	0.40%	0.24%	0.32%	0.40%	0.40%	0.32%
		DT10	0.38%	0.31%	0.38%	0.38%	0.38%	0.38%
		DT11	0.41%	0.25%	0.33%	0.41%	0.41%	0.33%
		DT12	0.20%	0.08%	0.12%	0.16%	0.16%	0.12%
		DT13	0.54%	0.22%	0.33%	0.54%	0.33%	0.43%
		DT14	0.35%	0.21%	0.35%	0.35%	0.35%	0.21%
		DT15	0.65%	0.52%	0.52%	0.52%	0.52%	0.52%
		DT16	0.43%	0.34%	0.26%	0.34%	0.34%	0.26%
		DT17	0.53%	0.32%	0.43%	0.53%	0.53%	0.43%
		DT18	0.53%	0.43%	0.43%	0.53%	0.53%	0.43%
		DT19	0.13%	0.08%	0.08%	0.13%	0.13%	0.10%
		DT20	0.35%	0.28%	0.21%	0.28%	0.28%	0.21%
		DT21	0.30%	0.24%	0.24%	0.24%	0.24%	0.24%
		DT22	0.21%	0.17%	0.17%	0.17%	0.17%	0.17%
		DT23	0.11%	0.04%	0.06%	0.09%	0.09%	0.06%
		DT24	0.80%	0.64%	0.64%	0.64%	0.64%	0.64%
		DT25	0.17%	0.14%	0.10%	0.14%	0.14%	0.10%
		DT26	0.16%	0.13%	0.13%	0.13%	0.13%	0.13%
		DT27	0.23%	0.09%	0.19%	0.23%	0.23%	0.19%
		DT28	0.23%	0.09%	0.19%	0.23%	0.23%	0.19%
		DT29	0.24%	0.20%	0.20%	0.24%	0.24%	0.20%
		DT30	0.13%	0.08%	0.05%	0.08%	0.08%	0.05%
		DT31	0.22%	0.13%	0.09%	0.18%	0.22%	0.13%

Figure A1. Sustainability details and index of cases.

Category	Subcategory	Label	RSW	Case 1	Case 2	Case 3	Case 4	Case 5
Element (21.7%)	Economic 14.30%	EEC1	0.21%	0.08%	0.08%	0.17%	0.17%	0.04%
		EEC2	0.50%	0.20%	0.50%	0.50%	0.40%	0.50%
		EEC3	1.03%	0.41%	0.62%	0.83%	0.83%	0.83%
		EEC4	0.24%	0.19%	0.10%	0.19%	0.15%	0.10%
		EEC5	0.14%	0.14%	0.09%	0.11%	0.09%	0.03%
		EEC6	0.34%	0.20%	0.27%	0.34%	0.27%	0.27%
		EEC7	0.47%	0.19%	0.37%	0.37%	0.28%	0.37%
		EEC8	0.17%	0.07%	0.13%	0.13%	0.13%	0.07%
	Environment 28.60%	EEN1	0.35%	0.28%	0.21%	0.28%	0.35%	0.21%
		EEN2	0.31%	0.12%	0.25%	0.31%	0.31%	0.19%
		EEN3	0.57%	0.34%	0.23%	0.34%	0.57%	0.23%
		EEN4	0.49%	0.20%	0.39%	0.39%	0.29%	0.29%
		EEN5	0.69%	0.28%	0.55%	0.69%	0.69%	0.69%
		EEN6	0.68%	0.41%	0.27%	0.54%	0.68%	0.27%
		EEN7	0.57%	0.23%	0.57%	0.57%	0.46%	0.57%
		EEN8	1.63%	0.98%	1.30%	1.30%	1.63%	0.98%
		EEN9	0.25%	0.10%	0.15%	0.15%	0.25%	0.10%
		EEN10	0.55%	0.22%	0.33%	0.55%	0.55%	0.44%
		EEN11	0.55%	0.22%	0.33%	0.55%	0.55%	0.33%
	Social 28.60%	ES1	0.48%	0.39%	0.10%	0.19%	0.10%	0.10%
		ES2	2.42%	2.42%	1.45%	1.45%	1.94%	1.45%
		ES3	2.42%	1.94%	1.45%	1.94%	1.94%	1.45%
	Technical 28.60%	ET1	0.61%	0.37%	0.61%	0.49%	0.37%	0.61%
		ET2	0.32%	0.25%	0.19%	0.25%	0.13%	0.13%
		ET3	1.18%	1.18%	0.71%	1.18%	0.95%	1.18%
		ET4	0.44%	0.27%	0.36%	0.36%	0.36%	0.18%
		ET5	1.12%	0.67%	0.89%	0.89%	0.89%	0.89%
		ET6	0.17%	0.13%	0.07%	0.10%	0.10%	0.07%
		ET7	0.16%	0.13%	0.03%	0.10%	0.10%	0.03%
		ET8	0.20%	0.04%	0.16%	0.20%	0.20%	0.20%
		ET9	0.54%	0.22%	0.32%	0.54%	0.32%	0.43%
		ET10	0.54%	0.32%	0.43%	0.43%	0.32%	0.54%
		ET11	0.54%	0.22%	0.32%	0.54%	0.32%	0.54%
		ET12	0.58%	0.35%	0.23%	0.47%	0.58%	0.35%
		ET13	0.23%	0.09%	0.23%	0.19%	0.14%	0.23%
Method (10.8%)	Economic 12.30%	MEC1	0.23%	0.18%	0.05%	0.14%	0.14%	0.05%
		MEC2	0.51%	0.21%	0.41%	0.41%	0.31%	0.31%
		MEC3	0.59%	0.24%	0.59%	0.59%	0.47%	0.59%
	Environment 25.10%	MEN1	0.33%	0.07%	0.20%	0.27%	0.33%	0.13%
		MEN2	0.62%	0.12%	0.49%	0.62%	0.62%	0.49%
		MEN3	0.62%	0.37%	0.37%	0.49%	0.49%	0.37%
		MEN4	1.15%	0.46%	0.92%	0.92%	0.92%	1.15%
	Social 12.10%	MS1	0.33%	0.26%	0.07%	0.13%	0.13%	0.07%
		MS2	0.77%	0.62%	0.31%	0.46%	0.62%	0.31%
		MS3	0.21%	0.17%	0.04%	0.12%	0.08%	0.04%
	Technical 50.40%	MT1	0.95%	0.57%	0.76%	0.76%	0.76%	0.76%
		MT2	0.99%	0.59%	0.99%	0.99%	0.79%	0.99%
		MT3	1.46%	1.46%	0.88%	1.46%	1.17%	1.46%
		MT4	0.34%	0.13%	0.34%	0.27%	0.27%	0.34%
		MT5	0.19%	0.11%	0.04%	0.15%	0.11%	0.04%
		MT6	0.19%	0.15%	0.04%	0.15%	0.11%	0.04%
		MT7	0.35%	0.28%	0.21%	0.21%	0.14%	0.14%
		MT8	0.98%	0.39%	0.78%	0.98%	0.78%	0.98%
Technology (19.7%)	Economic 19.70%	TEC1	0.39%	0.31%	0.23%	0.23%	0.23%	0.23%
		TEC2	0.95%	0.76%	0.57%	0.57%	0.57%	0.57%
		TEC3	0.85%	0.68%	0.51%	0.51%	0.51%	0.51%
		TEC4	1.70%	0.68%	1.36%	1.36%	1.36%	1.36%
	Environment 39.40%	TEN1	1.87%	0.75%	1.12%	1.87%	1.87%	1.12%
		TEN2	4.25%	1.70%	2.55%	4.25%	4.25%	2.55%
		TEN3	1.64%	0.66%	0.98%	1.31%	1.31%	0.98%
	Social 23.90%	TS1	1.88%	1.51%	1.51%	1.13%	1.13%	1.51%
		TS2	2.82%	1.13%	1.69%	2.26%	2.26%	1.69%
	Technical 16.90%	TT1	0.53%	0.42%	0.32%	0.21%	0.21%	0.32%
		TT2	1.28%	1.03%	0.77%	0.51%	0.51%	0.77%
		TT3	0.50%	0.40%	0.30%	0.20%	0.20%	0.30%
		TT4	1.02%	0.20%	0.41%	1.02%	1.02%	0.41%
Sustainability Index				**55.62%**	**68.38%**	**85.42%**	**83.30%**	**71.74%**

Figure A1 *Continued*

Table A1. AHP scores and RSW of CSFs within the housing design category and sub-categories.

Category	Subcategory	Critical Success Factor	Label	Score	Weight	Rank
Design (47.9%)	Economic 9.40%	Local value creation by design	DEC1	5.00%	0.23%	105
		Housing price in relation to income	DEC2	30.30%	1.36%	21
		Economy of scale mass production	DEC3	3.90%	0.18%	116
		Duration of design and construction	DEC4	10.50%	0.47%	72
		Lifecycle cost of house	DEC5	20.20%	0.91%	39
		Cost of house (design, construction and material cost)	DEC6	10.30%	0.46%	74
		Cost of operating	DEC7	8.80%	0.40%	79
		Cost of maintenance	DEC8	7.00%	0.32%	94
		Cost of demolition/recycling	DEC9	4.20%	0.19%	113
	Environment 29.10	Integrating renewable energy (solar geyser, PV, etc)	DEN1	4.50%	0.63%	48
		Lean design (minimising waste)	DEN2	2.40%	0.33%	90
		Integrating water recycling	DEN3	6.20%	0.86%	40
		Design with Local nature	DEN4	14.00%	1.95%	10
		Using energy efficient Systems/fittings	DEN5	8.70%	1.21%	24
		Using water efficient systems/fittings	DEN6	8.70%	1.21%	24
		Disaster resistance design	DEN7	18.60%	2.59%	5
		Integrating green building aspects	DEN8	5.20%	0.72%	44
		Using passive thermal	DEN9	10.50%	1.46%	19
		Using natural lighting	DEN10	10.60%	1.48%	17
		Using natural ventilation	DEN11	10.50%	1.46%	19
	Social 39.20%	Minimising social segregation	DS1	5.20%	0.98%	34
		Social acceptability of design	DS2	5.20%	0.98%	34
		Provide end-users' needs and satisfaction	DS3	12.90%	2.42%	6
		Aesthetic	DS4	2.80%	0.53%	65
		Privacy of house	DS5	15.90%	2.99%	3
		Comfortable and healthy indoor environment	DS6	11.00%	2.07%	9
		Compatible with local culture and lifestyle	DS7	6.90%	1.30%	22
		Tenure security	DS8	25.70%	4.83%	1
		Sense of Community	DS9	5.60%	1.05%	29
		Equality design (disabled, female, child, elderly)	DS10	8.90%	1.67%	14
	Technical 22.20%	Maintainability of design	DT1	3.70%	0.39%	80
		Flexibility of design	DT2	2.60%	0.28%	97
		Simplicity of design	DT3	1.20%	0.13%	123
		Compatibility of design with MMCs	DT4	1.80%	0.19%	112
		Design for disassembly	DT5	1.10%	0.12%	126
		Plumbing system/fittings	DT6	3.30%	0.35%	83
		Structural integrity	DT7	8.90%	0.95%	38
		Fire System (Escape)	DT8	4.60%	0.49%	70
		Drainage system	DT9	3.80%	0.40%	78
		Sanitation system/fittings	DT10	3.60%	0.38%	82
		Electrical system/fittings	DT11	3.90%	0.41%	77
		Heating and cooling system	DT12	1.90%	0.20%	110
		Insulation (thermal, water, noise, humidity)	DT13	5.10%	0.54%	58
		Building typology and orientation	DT14	3.30%	0.35%	83
		Economical design (floor area/plot area)	DT15	6.10%	0.65%	47
		Living area size (net floor area)	DT16	4.00%	0.43%	76

(*Continued*)

Table A1. Continued.

Category	Subcategory	Critical Success Factor	Label	Score	Weight	Rank
		Functionality of layout	DT17	5.00%	0.53%	62
		Adequate living spaces within small size unit	DT18	5.00%	0.53%	62
		Entrance design	DT19	1.20%	0.13%	123
		Bedrooms numbers, size	DT20	3.30%	0.35%	83
		Bathroom numbers, size/layout	DT21	2.80%	0.30%	96
		Kitchen size/layout	DT22	2.00%	0.21%	107
		Amenities	DT23	1.00%	0.11%	127
		Open space (yard, garden, balcony, green area)	DT24	7.50%	0.80%	42
		Storage	DT25	1.60%	0.17%	117
		Parking/ Garage	DT26	1.50%	0.16%	120
		Vertical circulation	DT27	2.20%	0.23%	101
		Horizontal circulation	DT28	2.20%	0.23%	101
		Link between indoor-outdoor spaces	DT29	2.30%	0.24%	99
		Able to install additional systems	DT30	1.20%	0.13%	123
		Facade	DT31	2.10%	0.22%	106

Table A2. AHP scores and RSW of CSFs within the housing element category and sub-categories.

Category	Subcategory	Critical Success Factor	Label	Score	Weight	Rank
Element (21.7%)	Economic	Local value creation by construction/assembly elements	EEC1	6.80%	0.21%	108
	14.30%	Economy of scale mass production of element	EEC2	16.10%	0.50%	67
		Lifecycle cost element	EEC3	33.30%	1.03%	30
		Material cost	EEC4	7.80%	0.24%	100
		Transport cost	EEC5	4.60%	0.14%	122
		Construction/ assembly cost	EEC6	10.90%	0.34%	88
		Maintenance cost	EEC7	15.00%	0.47%	73
		Demolition/recycling cost	EEC8	5.40%	0.17%	118
	Environment	Using local materials	EEN1	5.20%	0.35%	87
	30.60%	Recycling and deconstruction ability (circular economy)	EEN2	4.70%	0.31%	95
		Compatible with local nature	EEN3	8.60%	0.57%	54
		Effectively utilizing resources (virgin & recycled)	EEN4	7.40%	0.49%	69
		Water efficient	EEN5	10.40%	0.69%	45
		Minimise biodiversity loss	EEN6	10.20%	0.68%	46
		Waste efficient (lean)	EEN7	8.60%	0.57%	54
		Nontoxic	EEN8	24.50%	1.63%	16
		Using green material	EEN9	3.70%	0.25%	98
		Lifecycle Energy	EEN10	8.30%	0.55%	56
		Lifecycle GHG	EEN11	8.30%	0.55%	56
	Social	Local job creation by construction/assembly element	ES1	9.10%	0.48%	71
	24.50%	End user acceptance of element	ES2	45.50%	2.42%	7
		Cultural and heritage conservation	ES3	45.50%	2.42%	7
	Technical	Durability	ET1	9.20%	0.61%	51
	30.60%	Compatibility with other building components/ systems	ET2	4.80%	0.32%	93
		Standards/ building codes	ET3	17.80%	1.18%	26
		Adaptability/Flexibility	ET4	6.70%	0.44%	75
		Resilience	ET5	16.80%	1.12%	28
		Skill required for construction/assembly element	ET6	2.50%	0.17%	119

(*Continued*)

Table A2. Continued.

Category	Subcategory	Critical Success Factor	Label	Score	Weight	Rank
		Equipment and machinery required for construction/assembly	ET7	2.40%	0.16%	121
		Prefabrication/modularisation degree	ET8	3.00%	0.20%	111
		Thermal conductivity	ET9	8.10%	0.54%	59
		Water tightness	ET10	8.10%	0.54%	59
		Air tightness	ET11	8.10%	0.54%	59
		Acoustic	ET12	8.80%	0.58%	53
		Construction duration	ET13	3.50%	0.23%	103

Table A3. AHP scores and RSW of CSFs within the building method category and sub-categories.

Category	Subcategory	Critical Success Factor	Label	Score	Weight	Rank
Method (10.8%)	Economic	Local value creation by method	MEC1	17.00%	0.23%	104
	12.30%	Impact on the construction cost	MEC2	38.70%	0.51%	66
		Economy of scale of mass production of method	MEC3	44.30%	0.59%	52
	Environment	Minimising pollution and GHG emission	MEN1	12.30%	0.33%	91
	25.10%	Water efficient method	MEN2	22.70%	0.62%	49
		Energy efficient method	MEN3	22.70%	0.62%	49
		Minimising waste by method	MEN4	42.30%	1.15%	27
	Social	Community participation	MS1	25.20%	0.33%	92
	12.10%	Social acceptability of method	MS2	58.90%	0.77%	43
		Local job creation	MS3	15.90%	0.21%	109
	Technical	Interface to basic services	MT1	17.50%	0.95%	36
	50.40%	Reliability and durability	MT2	18.20%	0.99%	32
		Standards / manuals	MT3	26.90%	1.46%	18
		Impact on construction duration	MT4	6.20%	0.34%	89
		Skill required for construction method	MT5	3.40%	0.19%	114
		Equipment and machinery required	MT6	3.40%	0.19%	114
		Adaptability and flexibility with other methods	MT7	6.40%	0.35%	86
		Quality of workmanship	MT8	18.00%	0.98%	33

Table A4. AHP scores and RSW of CSFs within the technology category and sub-categories.

Category	Subcategory	Critical Success Factor	Label	Score	Weight	Rank
Technology (19.7%)	Economic	Initial cost of technology	TEC1	10.00%	0.39%	81
	19.70%	Operational cost of technology	TEC2	24.40%	0.95%	37
		Maintenance cost of technology	TEC3	21.90%	0.85%	41
		Impact of technology on operation or maintenance cost	TEC4	43.80%	1.70%	13
	Environment	Minimising waste by technology	TEN1	24.10%	1.87%	12
	39.40%	Minimising water and energy by technology	TEN2	54.80%	4.25%	2
		Improve air quality by technology	TEN3	21.10%	1.64%	15
	Social	Social acceptance of technology	TS1	40.00%	1.88%	11
	23.90%	Improve lifestyle by technology	TS2	60.00%	2.82%	4
	Technical	Availability of technology	TT1	15.90%	0.53%	64
	16.90%	Durability and Reliability of technology	TT2	38.50%	1.28%	23
		Skill requirement for using technology	TT3	14.90%	0.50%	68
		Decentralised services	TT4	30.60%	1.02%	31