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Research article

Sustainability evaluation of green building construction based on a combination method of weighting and improved matter-element extension

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Abstract: In light of the pressing global challenges related to greenhouse gas emissions from the construction industry, current evaluation systems for green building construction sustainability remain limited, often overlooking sustainability domains. This study innovatively established an evaluation framework by exploring five critical domains: environmental sustainability, economic benefits, socio-cultural impacts, technological innovation, and health and well-being. Sixteen key evaluation indicators were identified using the Delphi method, with the novel inclusion of a carbon emission reduction target achievement indicator, thereby promoting the goal of carbon neutrality in green buildings. To determine a more reasonable weight distribution, this paper combined the fuzzy analytic hierarchy process (fuzzy AHP) with the entropy weight method. Additionally, the study employed a fuzzy matter-element method enhanced by genetic algorithms for precise evaluation of green building construction sustainability. The feasibility and effectiveness of the proposed model were validated through an empirical analysis of a green building project in Beijing. The results of this research provide innovative theoretical references and practical guidelines for green building construction sustainability evaluation.

Keywords: green buildings; sustainability evaluation; Delphi method; fuzzy matter-element method; combination weighting method
Mathematics Subject Classification: 62P30

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1. Introduction

As global climate change issues become increasingly severe, greenhouse gas emissions from the construction industry have become one of the major sources of global carbon emissions [1]. Statistics indicate that the construction industry accounts for approximately one-third of the total global carbon emissions, positioning it at the forefront of global efforts to reduce carbon emissions. Green buildings, as an emerging architectural concept, aim to achieve environmental sustainability and economic benefits throughout the building's lifecycle by optimizing resource use and reducing environmental pollution [2]. Globally, green buildings are widely recognized as a crucial approach to addressing climate change and achieving sustainable development [3].

As a significant source of global energy consumption and carbon emissions, the construction industry faces substantial environmental pressures and social responsibilities. In recent years, various countries have introduced a series of policies and standards to promote the development of green, low-carbon, and sustainable practices in the construction sector. For instance, the United States introduced the leadership in energy and environmental design (LEED) standard to encourage energy-efficient and sustainable buildings [4]; the European Union implemented the energy performance of buildings directive (EPBD), which requires new buildings to achieve near-zero energy standards [5]; China released the green building evaluation standard (GBES), which covers environmental impact assessments throughout the building's lifecycle [6]; Japan implemented the comprehensive assessment system for built environment efficiency (CASBEE) system for comprehensive environmental performance assessments of buildings [7]; and Australia established the national Australian built environment rating system (NABERS) and the building energy efficiency act (BEEA) to promote building energy efficiency assessments and carbon emission reductions [8]. These policies and standards have not only heightened awareness of building energy efficiency and environmental protection in various countries but also provided valuable insights for the global development of green buildings. Green buildings must not only meet basic environmental sustainability requirements but also possess comprehensive advantages in economic benefits, socio-cultural impacts, technological innovation, and health and well-being. However, the issue of sustainability in green building construction has increasingly garnered attention. Traditional evaluation systems primarily focus on building quality and safety during the construction process, neglecting the broader environmental impacts and sustainability requirements [9]. Establishing a comprehensive sustainability evaluation system for green building construction can not only assess potential safety hazards but also promote holistic development, considering environmental, economic, socio-cultural, technological, and health aspects. This paper aims to establish a comprehensive sustainability evaluation framework for green building construction, providing a scientific basis for the holistic assessment of green building construction.

Currently, global green building evaluation standards are being continuously refined to include key indicators like carbon emission assessments. While these standards emphasize environmental impact and resource efficiency across all building phases, there is a gap in comprehensive assessment during the construction phase. Most existing systems focus on the operational phase and neglect carbon emissions and environmental impacts during construction. This lack of integrated, systematic, and scientific evaluation methods poses a significant challenge.

Research questions and objectives:

(1) How can we develop a comprehensive sustainability evaluation framework that effectively includes carbon emission assessments during the construction phase of green buildings? (2) What are the critical evaluation indicators necessary for a holistic assessment of green building construction sustainability? (3) How can advanced methodologies improve the precision and applicability of sustainability assessments for green building construction?

To address these questions, this paper introduces a sustainability evaluation framework for green building construction, focusing on achieving carbon emission targets. The Delphi method was employed to identify 16 critical evaluation indicators. To ensure a balanced weight distribution, the fuzzy analytic hierarchy process (fuzzy AHP) and entropy weight method were combined. An improved fuzzy matter-element method enhanced by genetic algorithms was then applied to develop a comprehensive evaluation model. The model's validity and feasibility were demonstrated through a green building project in Beijing.

Key innovations of this research include:

- Introduction of the carbon emission target achievement indicator: Traditional green building evaluation systems often overlook carbon emissions during the construction phase, resulting in an incomplete assessment of the project's sustainability. This study introduces the novel carbon emission target achievement indicator, which specifically evaluates carbon emissions during the construction phase. This innovation advances the understanding and implementation of carbon reduction strategies in green building projects, addressing a critical gap in existing evaluation systems.
- Application of an enhanced fuzzy matter-element method with genetic algorithms: Traditional fuzzy matter-element methods often struggle with complex and uncertain data, limiting their effectiveness in green building construction sustainability assessments. This study presents an innovative application of a genetic algorithm-enhanced fuzzy matter-element method. By optimizing model parameters to better handle complex data, this approach significantly improves the precision and reliability of evaluation results. This enhancement increases the model's feasibility for practical applications, providing a robust tool for sustainability assessments.
- Development of a comprehensive sustainability evaluation framework: This study establishes a novel and comprehensive framework for the sustainability evaluation of green building construction. By integrating environmental, economic, socio-cultural, technological, and health-related indicators, the framework offers a holistic approach to assessing and promoting sustainability in green building projects. This comprehensive evaluation model addresses the need for an inclusive assessment system that guides sustainable practices throughout the construction process, offering a significant advancement over existing fragmented and narrow evaluation methods.

The structure of this paper is as follows. Section 2 provides an overview of the current state of research on sustainability evaluation indicator systems and methods for assessing green building construction. Section 3 outlines the research methods used in this study, including the Delphi method, fuzzy AHP, entropy weight method, and the genetic algorithm-enhanced fuzzy matter-element method. Section 4 presents the empirical analysis of a green building project in Beijing. The final section discusses the significance, limitations, and future directions of this research.

2. Literature review

Sustainability evaluation of green building construction not only pertains to the quality and safety of buildings but also has significant implications for environmental protection and sustainable development. Although extensive research has explored sustainability evaluation frameworks and assessment methods for green building construction, the practical application remains challenging. Therefore, it is necessary to systematically review and analyze existing research to identify its strengths and weaknesses and to explore directions for further optimization.

2.1. Building construction evaluation index system

With increasing global emphasis on environmental protection and sustainable development, the evaluation index system for green building construction sustainability has gradually become a focal point of research. Numerous studies have endeavored to develop scientifically robust index systems to comprehensively assess the sustainability impacts during the green building construction process. Current research mainly focuses on areas such as environmental sustainability, economic benefits, socio-cultural impacts, technological innovation, and health and well-being. For instance, Adewumi et al. (2024) proposed an environmental sustainability index system for green building construction based on life cycle assessment, which includes key indicators such as energy consumption, water usage, and waste emissions [10]. Kamali et al. (2023) established an evaluation framework that considers economic benefits by analyzing construction costs and energy-saving effects to assess the economic feasibility of construction [11]. Nandita et al. (2023) examined the impact of green building construction on local communities and socio-cultural aspects, proposing a set of socio-cultural impact evaluation indicators [12]. Dubljevic et al. (2024) introduced a technological innovation index system to evaluate the effectiveness of new technologies in green building construction [13]. Chen et al. (2022) developed a health and well-being evaluation index that monitors health risks in the construction environment to ensure safety and health during the construction process [14]. These studies have made significant progress in developing evaluation index systems, providing a scientific basis and practical guidance for assessing green building construction sustainability.

Recent studies have further enriched the evaluation framework for green building construction. For example, Fan et al. (2024) [15] proposed a green assessment method for prefabricated buildings in China using the decision-making trial and evaluation laboratory (DEMATEL) optimization technique. This method defines the evaluation index system based on green design, intelligent construction, assembled building quality, and comprehensive benefits, optimizing the index weight using the analytic hierarchy process-entropy weight method (AHP-EWM) method. This comprehensive approach ensures a nuanced and precise sustainability assessment of prefabricated buildings. Zhang (2024) [16] explored the application of the building information modeling (BIM) technology in green building design using neural network learning. By integrating BIM with artificial neural networks, this study developed a comprehensive evaluation system that addresses the risk assessment and sustainability evaluation of green building projects, significantly enhancing the evaluation's accuracy and applicability. Pan et al. (2024) [17] introduced a multi-objective optimization framework for green building design using deep reinforcement learning. This framework optimizes design parameters by incorporating a deep neural network model, demonstrating substantial improvements in building performance through a case study in Shanghai.

However, current research on the evaluation index system for green building construction sustainability still has some limitations. First, many studies primarily focus on static environmental and economic indicators without accounting for the dynamic changes and real-time data during the construction process. This lack of dynamism makes it challenging to capture the ongoing sustainability impacts effectively. Second, the existing socio-cultural and health and well-being indicators often rely heavily on qualitative assessments, which lack the robust quantitative data needed to enhance the objectivity and reliability of the evaluation results. Finally, many economic benefit index systems tend to overlook the long-term financial impacts, such as maintenance and operational costs, thereby providing an incomplete assessment of the economic sustainability of green buildings.

To address these issues of static, fragmented, and predominantly qualitative analysis in existing green building construction sustainability evaluation index systems, this paper employs a comprehensive approach incorporating the Delphi method. The Delphi method is utilized to identify key evaluation indicators for green building construction sustainability through multiple rounds of expert surveys. This process gathers the collective wisdom and experience of experts to ensure the indicators' scientific rigor and comprehensiveness. The systematic collection and integration of expert opinions help to avoid biases from individual perspectives, and through iterative feedback and refinement, a well-rounded and precise evaluation index system is established.

Compared to traditional static and single-dimensional index systems, the Delphi method, combined with real-time data integration techniques, better captures the dynamic changes and multidimensional impacts during the green building construction process. This provides a robust scientific basis for a more comprehensive and adaptive assessment of construction sustainability. Additionally, the iterative nature of the Delphi method ensures that the identified indicators are highly operable and practical in real-world applications, effectively addressing the shortcomings of excessive qualitative analysis and insufficient quantitative data in current research.

2.2. *Green building construction assessment methods*

Existing green building construction sustainability assessment methods primarily include fuzzy comprehensive evaluation, grey system theory, and matter-element methods. The fuzzy comprehensive evaluation method deals with each indicator through fuzzification, combining expert opinions and actual data to address sustainability assessment issues in complex environments [18]. For example, Wang et al. (2023) constructed an evaluation index system for green building supply chain resilience and used the interpretative structural model to analyze the correlation between evaluation indexes. They established an ANP-fuzzy comprehensive evaluation model to assess the resilience of the green building supply chain, and their empirical study on a project in Jiaozuo City demonstrated the model’s effectiveness in practical case analysis [19]. The grey system theory is used to handle uncertain and incomplete information, effectively evaluating construction risks through grey relational analysis [20]. Lyu et al. (2023) proposed a reciprocal symbiosis evaluation index model based on urban ecology theory to enhance green building management in eco-cities. They used the expert survey method to determine evaluation indicators and analyze the relationships between various city subsystems [21]. The matter-element method is a system evaluation method based on the matter-element theory that quantifies evaluation indicators to construct a comprehensive evaluation model [22]. This method is particularly suited for handling complex and variable evaluation systems. Zhang et al. (2023) improved the evaluation index system for green building operation effects and established a comprehensive evaluation model using a grey clustering-fuzzy comprehensive evaluation method [23].

Recent studies have also highlighted the economic evaluation of retrofitting existing buildings from a sustainability perspective. Kong et al. (2024) [24] conducted a bibliometric study analyzing 246 publications using the CiteSpace application, which explored key aspects such as sustainable development goals, interdisciplinary convergence, and international collaboration in building retrofitting. Their findings revealed core keywords and identified three research directions: economic analysis, management evaluation, and climate impact assessment, which are crucial for the future development of sustainable building practices.

Additionally, the research on green building rating systems has gained prominence, especially under the background of carbon peaking and carbon neutrality. Mao et al. (2024) [4] systematically summarized the progress of green building rating systems (GBRS) in weight setting, indicator setting, and the evaluation process. They proposed future research directions including the use of machine learning and deep learning models for weight determination, the integration of dynamic evaluation indicators, and the combination of building information modeling with GBRS to improve evaluation comprehensiveness and accuracy.

Objective weighting methods are based on data and objective statistics, such as the entropy weight method and the coefficient of variation method. These methods determine weights by analyzing the statistical characteristics of each indicator, such as data dispersion or volatility [25]. For instance, the entropy weight method calculates information entropy to reflect the information content and variability of each indicator, thus avoiding human interference. Although objective weighting methods can effectively reduce subjective bias, they require high-quality data, and incomplete or poor-quality data can affect the accuracy of weight calculations [26]. Combined weighting methods integrate subjective and objective weighting, balancing expert experience and data objectivity to ensure the scientific and rational distribution of weights [27]. This approach leverages expert knowledge and judgment while enhancing the objectivity and accuracy of results through data analysis. In existing research, combined weighting methods have gained widespread attention and practical application in green building construction models. Zheng et al. (2022) proposed a combined model based on grey theory and neural networks for the design of green building materials reinforcement, effectively addressing complex uncertainties and improving building safety and sustainability by combining the advantages of grey theory and neural network models [28]. Ma et al. (2021) applied a combined method of fuzzy AHP and the entropy weight method to comprehensively evaluate the green building construction model, addressing the inadequacies of single methods in fully considering expert experience and data objectivity, thus enhancing the reliability and accuracy of evaluation results [29]. Yin et al. (2019) combined the entropy weight method with the VIšekriterijumsko KOmpromisno Rangiranje (VIKOR) and modified ELimination and Choice Expressing Reality (ELECTRE) methods, using the entropy weight method to calculate standard weights and integrating the compensatory and non-compensatory decision rules of the VIKOR and ELECTRE methods [30].

Despite the effectiveness of current green building construction sustainability assessment methods in practice, there are still some limitations. The fuzzy comprehensive evaluation method has constraints in handling dynamic data changes, making it difficult to reflect changes during the construction process in real-time [22]. The grey system theory is highly dependent on data, and its accuracy and adaptability can be compromised when data is missing or incomplete [20]. Life cycle assessment mainly relies on static data and lacks consideration of real-time data during the construction process, failing to dynamically reflect changes and potential risks during construction [31]. The matter-element method, although capable of considering multiple evaluation factors, faces challenges in handling large-scale and real-time data, particularly in complex construction environments where its application may be affected by data quality and model complexity [32].

Nevertheless, these studies indicate that combined weighting methods can effectively consider multiple influencing factors, demonstrating significant advantages in green building construction sustainability assessment. This approach addresses the shortcomings of single-weighting methods in handling complex multidimensional data, and by integrating expert opinions and objective data, enhances the scientific and practical nature of the evaluation system. This paper chooses to combine the fuzzy AHP with the entropy weight method. Fuzzy AHP effectively addresses the uncertainty and ambiguity in expert opinions, ensuring the scientific distribution of weights. The entropy weight method, based on objective data, reduces the impact of subjective bias in weight allocation. This combination leverages the advantages of both methods, ensuring the scientific and objective nature of the evaluation system and improving the accuracy and practicability of evaluation results. Furthermore, this paper innovatively applies a genetic algorithm-enhanced fuzzy matter-element method, optimizing model parameters to improve the handling of complex data and the accuracy of assessment results, thereby further enhancing the scientific and practical nature of green building construction sustainability assessment.

3. Materials and methods

This study employs a series of scientific methods to effectively address the complexities involved in evaluating the sustainability of green building construction based on achieving carbon emission targets. Initially, a detailed evaluation index system for green building construction sustainability was developed using the Delphi method. Following the determination of evaluation indicators, a combined approach of fuzzy AHP and the entropy weight method was utilized to establish the weights for each indicator. Subsequently, a genetic algorithm-enhanced fuzzy matter-element method was applied for the precise evaluation of green building construction sustainability. The research methodology is illustrated in Figure 1.

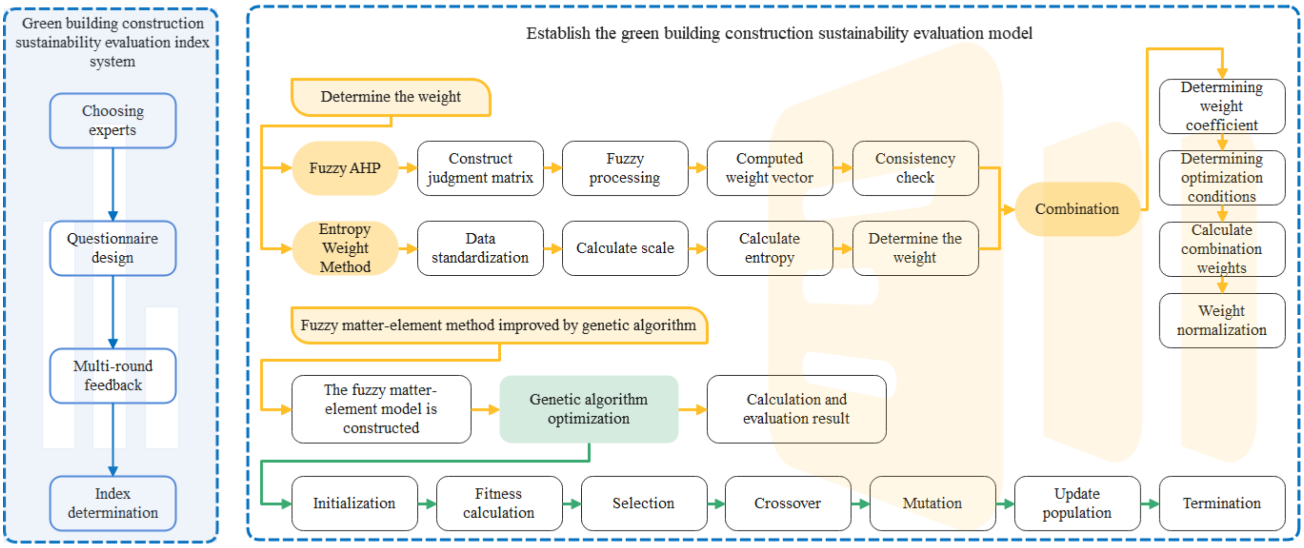

Figure 1. Research methodology framework.

3.1. Development of the evaluation index system

In the selection of evaluation indicators, the principles of comprehensiveness, scientific rigor, systematic approach, and operability were adhered to. Initially, potential evaluation indicators were identified through a thorough review of relevant literature on green building construction sustainability [33]. To ensure the scientific validity and authority of these indicators, the Delphi method was employed for further screening and determination. The Delphi method, a systematic evaluation technique based on expert opinions, achieves expert consensus through multiple rounds of anonymous questionnaires, thereby minimizing the influence of individual expert biases. This method is particularly valuable in integrating diverse expert knowledge and ensuring that the selected indicators are both comprehensive and applicable to various aspects of green building construction. The specific steps undertaken in the Delphi method were as follows:

(1) Expert Selection: Ten experts with extensive experience in the fields of green building and construction sustainability were selected. These experts included representatives from academia, construction enterprises, and government departments. Their diverse backgrounds ensured a broad perspective on the key factors affecting green building sustainability [34].

(2) Initial Indicator Identification: Based on an extensive literature review, several evaluation dimensions were preliminarily identified, including environmental sustainability, economic benefits,

socio-cultural impacts, technological innovation, and health and well-being. Potential evaluation indicators were listed under each dimension, drawing from existing frameworks and recent studies.

(3) Questionnaire Design and Distribution: The initial list of indicators was compiled into a questionnaire, which was then distributed to the selected experts. Each expert was asked to rate the importance of each indicator on a scale and provide feedback on their relevance and applicability [35].

(4) Multiple Rounds of Feedback and Consensus Building: Through three rounds of questionnaires, the experts rated and provided feedback on the importance of each indicator. After each round, the results were statistically analyzed, and the feedback was used to refine and improve the indicator system. This iterative process continued until a consensus was reached on the most relevant and impactful indicators [36].

(5) Indicator Determination: In the application of the Delphi method, multiple rounds of expert opinion collection and analysis led to the final determination of 16 key evaluation indicators for green building construction sustainability, as illustrated in Figure 2. These indicators cover the five main areas of environmental sustainability [37], economic benefits [38], socio-cultural impacts [39], technological innovation [40], and health and well-being [41]. Notably, the carbon emission target achievement indicator was introduced to comprehensively evaluate carbon emissions during the construction phase, promoting the goal of carbon neutrality in green buildings.

It is noteworthy that the carbon emission reduction target achievement indicator is introduced to comprehensively evaluate carbon emissions during the construction phase, thereby promoting the goal of carbon neutrality in green buildings. Although existing evaluation systems have incorporated factors such as carbon emissions, they often focus solely on the operational phase, neglecting emissions during the construction phase. This oversight results in an incomplete assessment of the project’s overall environmental impact, particularly as emissions during construction can be significant but are insufficiently accounted for. Additionally, existing systems lack effective methods for quantifying and tracking the achievement of carbon reduction targets, making it difficult to specifically evaluate and improve carbon reduction efforts during the construction phase. By introducing the carbon emission reduction target achievement indicator, this study addresses existing shortcomings and provides a new dimension for the evaluation of green building projects. This indicator comprehensively assesses carbon emissions during the construction phase, ensuring that carbon reduction efforts are effectively recorded and evaluated. By quantifying the achievement of carbon reduction targets, this indicator enables projects to clearly identify their carbon emissions during construction and develop more targeted reduction strategies, thereby enhancing overall sustainability. Furthermore, the carbon emission reduction target achievement indicator helps align green building projects with global carbon neutrality goals. Given that the construction industry is a major contributor to greenhouse gas emissions, incorporating an indicator specifically focused on carbon reduction achievements is crucial. This aids in tracking progress toward sustainability goals and provides a clear benchmark for future projects.

Beyond environmental benefits, achieving carbon reduction targets can also lead to economic advantages through energy savings and reduced operational costs. Socially, it demonstrates a commitment to sustainable development, enhancing the project’s reputation and acceptance among stakeholders and the community.

Category	NO.	Indicator	Quantification Method	Unit
Environmental Sustainability	E$_1$	Carbon Reduction Goal Achievement	Calculate the percentage of achieved carbon reduction target relative to the baseline emissions.	%
	E$_2$	Energy Consumption	Measure the total energy used during the construction phase.	MJ (MegaJoules)
	E$_3$	Water Resource Utilization Efficiency	Calculate water used per unit area of construction.	L/m^2 (Liters per square meter)
	E$_4$	Waste Management	Measure the percentage of construction waste recycled or properly managed.	%
	E$_5$	Ecological Protection Measures	Evaluate the area of ecological damage mitigated through conservation measures.	m^2 (square meters)
Economic Benefits	E$_6$	Construction Cost Control	Compare the actual construction cost against the budgeted cost.	% deviation from budget
	E$_7$	Long-term Operating Costs	Calculate the estimated annual operating costs over the building's lifetime.	USD/year
	E$_8$	Economic Return Rate	Measure the internal rate of return (IRR) on the project investment.	%
Socio-cultural Impact	E$_9$	Community Impact	Evaluate the number of complaints or disruptions reported by the community.	Count
	E$_{10}$	Cultural Resource Protection	Measure the number of cultural resources preserved or enhanced during construction.	Count
Technological Innovation	E$_{11}$	Application of Green Construction Technologies	Calculate the percentage of green technologies implemented in the project.	% of total technologies
	E$_{12}$	Safety of Construction Technologies	Assess the frequency of safety incidents related to construction technologies.	Incidents per 1000 hours
	E$_{13}$	Smart Management Systems	Measure the extent of smart management systems used (e.g., automated monitoring systems).	% coverage
Health and Well-being	E$_{14}$	Construction Safety Management	Calculate the accident rate per 100,000 hours worked.	Accidents per 100,000 hours
	E$_{15}$	Health Impact of Construction Environment	Evaluate the concentration of pollutants and hazardous substances at the construction site.	mg/m^3 (milligrams per cubic meter)
	E$_{16}$	Health Environment during Operation	Measure indoor air quality parameters such as CO2 concentration, temperature, and humidity.	Various (e.g., ppm for CO2, °C for temperature, % for humidity)

Figure 2. Green building construction sustainability evaluation index system.

3.2. Development of the evaluation model

After constructing a comprehensive evaluation index system for green building sustainability, a combined weighting method was employed to accurately reflect the importance of each indicator within the evaluation system. This method integrated the fuzzy AHP with the entropy weight method, achieving rational weighting for each evaluation indicator. The approach not only considered subjective factors from expert opinions but also introduced objectivity through data analysis, resulting in a more scientific and accurate weight distribution. Fuzzy AHP is an extension of traditional AHP, which incorporates fuzzy logic to handle the inherent uncertainty and subjectivity in expert judgments. Traditional AHP relies on precise numerical values for pairwise comparisons, which can be challenging in complex decision-making scenarios where expert opinions may be vague or imprecise. Fuzzy AHP addresses this by using fuzzy numbers instead of exact values, allowing for a more flexible and realistic representation of expert judgments [42]. The specific steps are as follows [43]:

Step 1. Constructing the Judgment Matrix: Initially, ten experts in the field of green building were invited to compare the relative importance of each pair of evaluation indicators, forming a judgment matrix. The judgment matrix A is an $n \times n$ matrix representing the relative importance of each indicator. Here, n is the number of indicators and the elements a_{ij} in the matrix represent the importance of indicator i relative to indicator j as assessed by the experts.

$$A = \begin{pmatrix} 1 & a_{12} & \cdots & a_{1n} \\ \frac{1}{a_{12}} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{a_{1n}} & \frac{1}{a_{2n}} & \cdots & 1 \end{pmatrix}. \tag{1}$$

Step 2. Fuzzification: The expert judgments are fuzzified to generate a fuzzy judgment matrix A_f. The elements $\tilde{a}_{ij}$ in the fuzzy judgment matrix A_f are fuzzy numbers used to reflect the uncertainty and vagueness of the experts' opinions.

$$A_f = \begin{pmatrix} 1 & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \frac{1}{\tilde{a}_{12}} & 1 & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{\tilde{a}_{1n}} & \frac{1}{\tilde{a}_{2n}} & \cdots & 1 \end{pmatrix}. \tag{2}$$

Step 3. Weight Vector Calculation: The relative weights w_i for each indicator are obtained by solving for the largest eigenvalue λ_{max} and its corresponding eigenvector of the fuzzy judgment matrix. The weight vector w_i represents the relative importance of the i-th indicator.

$$w_i = \frac{\sum_{j=1}^{n} \tilde{a}_{ij}}{\sum_{i=1}^{n} \sum_{j=1}^{n} \tilde{a}_{ij}}. \tag{3}$$

Step 4. Consistency Check: The consistency ratio (CR) of the judgment matrix is calculated to verify the reasonableness of the expert judgments. If the consistency ratio CR is less than 0.1, the consistency of the judgment matrix is considered acceptable. Here, CI is the consistency index, and RI is the random consistency index.

$$CR = \frac{CI}{RI}. \tag{4}$$

The entropy weight method is an objective weighting technique based on information theory, used to determine the weights of indicators by analyzing the dispersion and variability of the data. It reduces the impact of subjective biases and enhances the objectivity of the weighting process [44]. The steps are as follows [45]:

Step 1. Data Standardization: The data for each indicator are normalized to eliminate unit differences. The standardized data x_{ij} are calculated using the following formula:

$$x_{ij} = \frac{x_{ij} - min(x_j)}{max(x_j) - min(x_j)}. \tag{5}$$

Step 2. Proportion Calculation: The proportion p_{ij} of each standardized indicator value in the total sample is calculated.

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}}. \tag{6}$$

Step 3. Entropy Calculation: The information entropy e_j for each indicator is calculated to measure its dispersion. Here, e_j represents the information entropy of the j-th indicator, and k is a constant used to normalize the entropy value.

$$e_j = -k \sum_{i=1}^{m} p_{ij} \ln(p_{ij}),\ k = \frac{1}{\ln(m)}. \tag{7}$$

Step 4. Weight Determination: The difference degree g_j is calculated based on the information entropy value, and the objective weights of each indicator are determined. Here, g_j is the difference coefficient of the j-th indicator, and w_j is the objective weight of the j-th indicator.

$$g_j = 1 - e_j \tag{8}$$

$$w_j = \frac{g_j}{\sum_{j=1}^{n} g_j}. \tag{9}$$

By using the entropy weight method, the influence of subjective judgments is minimized, and the weights are derived purely based on the inherent characteristics of the data. This method is particularly useful when objective data is available, and it complements the fuzzy AHP by adding a layer of objectivity to the weighting process.

The combined use of fuzzy AHP and the entropy weight method provides a balanced approach to determining the weights of evaluation indicators. The fuzzy AHP effectively addresses the uncertainty and subjectivity in expert opinions, ensuring a comprehensive and rational distribution of weights based on expert knowledge and experience. On the other hand, the entropy weight method introduces objectivity by relying on data analysis, reducing the potential biases from subjective judgments.

This dual approach leverages the strengths of both methods, resulting in a scientifically robust and practically applicable evaluation framework for green building sustainability. By integrating subjective and objective perspectives, the combined weighting method ensures that the evaluation indicators reflect a holistic understanding of green building sustainability, enhancing the accuracy and reliability of the assessment. To comprehensively consider both subjective and objective factors, a combined weighting method was adopted, integrating the fuzzy AHP and the entropy weight methods. The specific steps are as follows:

Step 1. Weight Coefficient Determination: The values of α and β are determined through an optimization model. α and β represent the weighting coefficients for subjective and objective weights, respectively, and they satisfy $\alpha + \beta = 1$. The optimization model can be solved using the Lagrange multiplier method, where x_k is the value of the k-th indicator.

$$maxF(\alpha, \beta) = \sum_{k=1}^{n} (\alpha w_k' + \beta w_k'')x_k. \tag{10}$$

Step 2. Optimization Conditions Determination: The optimization process can balance the influence of subjective and objective weights by setting different objective functions and constraints.

$$\alpha^2 + \beta^2 = 1. \tag{11}$$

Step 3. Combined Weight Calculation: The final combined weight w_k^* is calculated based on the optimized values of α and β.

$$w_k^* = \alpha w_k' + \beta w_k''. \tag{12}$$

Step 4. Weight Normalization: The combined weights are normalized to ensure that the sum of all weights equals 1. The normalized combined weight w_k^* is calculated using the following formula:

$$w_k^* = \frac{w_k^*}{\sum_{k=1}^{n} w_k^*}. \tag{13}$$

After determining the weights, an innovative evaluation model for green building construction sustainability was developed, utilizing a genetic algorithm-enhanced fuzzy matter-element method for assessment. The genetic algorithms were employed to optimize the parameters of the fuzzy matter-element model, enhancing its ability to handle complex and variable data, thereby improving the precision and reliability of the evaluation results. Genetic algorithms contribute to the precision of the evaluation by optimizing the fuzzy matter-element model through several key steps:

(1) Initialization: A population of potential solutions (chromosomes) is generated randomly. Each chromosome represents a set of parameters for the fuzzy matter-element model, such as membership functions and weights. This diversity ensures a broad search space for optimal solutions.

(2) Fitness Evaluation: The fitness of each chromosome is evaluated using a predefined fitness function, which measures how well each set of parameters performs in terms of evaluation accuracy and consistency with expert judgments and empirical data. This step ensures that only the most effective solutions are retained.

(3) Selection: The selection process involves choosing the fittest chromosomes to be parents for the next generation. Techniques such as roulette wheel selection or tournament selection are used to ensure that chromosomes with higher fitness have a higher probability of being selected. This step enhances the model's robustness by prioritizing better-performing solutions.

(4) Crossover: The crossover operation combines pairs of parent chromosomes to produce offspring. This involves exchanging segments of the parents' chromosomes to create new combinations of parameters, promoting genetic diversity in the population. Common crossover methods include single-point, multi-point, and uniform crossover.

(5) Mutation: The mutation operation introduces random changes to the chromosomes, altering some of their genes to explore new solutions and prevent premature convergence. This step ensures that the algorithm can escape local optima and find the global optimum. Mutation methods include bit-flip mutation, swap mutation, and inversion mutation.

(6) Replacement: The new generation of chromosomes, created through crossover and mutation, replaces the old generation. This iterative process continues, with each generation expected to yield better solutions due to the evolutionary operators applied.

(7) Termination: The algorithm iterates through the selection, crossover, mutation, and replacement steps until a termination criterion is met, such as reaching a maximum number of generations, achieving a desired level of fitness, or observing no significant improvement in fitness over successive generations.

By integrating genetic algorithms with the fuzzy matter-element method, the evaluation model benefits from the robust search capabilities of GAs. This enhancement allows the fuzzy matter-element method to adaptively fine-tune its parameters, improving the accuracy and consistency of the sustainability evaluation for green building construction. The optimized model can better handle the uncertainties and complexities inherent in real-world data, leading to more precise and reliable assessment outcomes. The specific steps are as follows:

Step 1. Constructing the Fuzzy Matter-Element Model: Matter-element theory is used to quantify evaluation indicators and to construct a comprehensive evaluation model. The matter-element model is defined as follows, where R_j is the j-th matter-element, N_j is the evaluation grade, C_j is the evaluation indicator, and V_{ji} is the value range of the i-th indicator:

$$R_j = (N_j, C_j, V_{ji}) = \begin{bmatrix} N_j & c_1 & \langle a_{j1}, b_{j1} \rangle \\ & c_2 & \langle a_{j2}, b_{j2} \rangle \\ & \vdots & \vdots \\ & c_n & \langle a_{jn}, b_{jn} \rangle \end{bmatrix}. \tag{14}$$

Step 2. Genetic Algorithm Optimization: The genetic algorithm is used to optimize the fuzzy matter-element model, enhancing the model's ability to handle complex data and improving the accuracy of evaluation results. Initially, a random initial population $P(t)$ of size n is generated. Then, the fitness value $f(x)$ for each individual is calculated to evaluate its performance in the model. Selection is based on fitness values, retaining individuals with higher fitness probabilities, denoted as p. Selected individuals undergo crossover operations with a crossover probability p_c, generating new individuals. These new individuals undergo mutation operations with a mutation probability p_m, increasing population diversity. The new individuals are then added to the population to form the next generation $P(t+1)$. This process continues until the preset number of generations T is reached or the termination conditions are satisfied, ultimately outputting the optimal solution. The fitness calculation formula is as follows, where x represents an individual, $f(x)$ represents the fitness value, w_i is the weight of the i-th indicator, and $g(x_i)$ is the value of the i-th indicator:

$$f(x) = \sum_{i=1}^{n} w_i \cdot g(x_i). \tag{15}$$

Step 3. Calculation of Evaluation Results: To calculate the evaluation results, all evaluation indicators are first standardized to bring each indicator's value to the same scale. This is done using the standardization formula:

$$X_{ij}^{*} = \frac{X_{ij} - X_{min}}{X_{max} - X_{min}}, \tag{16}$$

where X_{ij} represents the value of the i-th indicator for the j-th evaluation object, and X_{min} and $X_{\max}$ are the minimum and maximum values for that indicator, respectively.

Next, a comprehensive evaluation function is constructed based on the fuzzy matter-element model to calculate the overall score for each evaluation object. The evaluation function formula is:

$$S_i = \sum_{j=1}^{n} w_j \cdot F(V_{ij}), \tag{17}$$

where S_i is the comprehensive score of the i-th evaluation object, w_j is the weight of the j-th indicator, and $F(V_{ij})$ is the standardized value of the i-th evaluation object on the j-th indicator.

Finally, by integrating the scores of each indicator, the final grading and ranking are conducted. The grading formula is:

$$K_i = \sum_{j=1}^{n} \left(\frac{S_i - a_{ij}}{b_{ij} - a_{ij}} \right) \cdot w_j, \tag{18}$$

where K_i is the final grade score of the i-th evaluation object, and a_{ij} and b_{ij} are the minimum and maximum values of the i-th object on the j-th indicator. Through these steps, a scientific evaluation of green building construction sustainability is achieved.

Through the above methods, a systematic evaluation model for green building construction sustainability has been constructed, effectively addressing the limitations of existing evaluation methods and providing new insights and approaches for the scientific evaluation of green building construction sustainability.

4. Case studies

This section presents an empirical analysis of a green building project in Beijing to validate the feasibility and effectiveness of the proposed green building construction sustainability evaluation model. As one of China's key infrastructure projects to receive advanced energy-saving certification, this project has significant demonstrative importance in energy conservation, emission reduction, environmental protection, and sustainability. With the core principles of "green, low-carbon, intelligent, and intensive", the project aims to achieve internationally leading standards in energy consumption, carbon emissions, and environmental protection.

As a significant public infrastructure project, the construction has consistently adhered to the latest national green building evaluation standards, emphasizing environmental sustainability and economic viability, while strictly controlling carbon emissions and resource consumption during the construction process. The focus of this case study is a key building within the project, which has achieved significant reductions in energy consumption and carbon emissions. The project demonstrates its commitment to sustainability through the use of renewable energy and strict adherence to environmental standards, making it an ideal candidate for applying the sustainability evaluation model for green building construction developed in this study. The following section provides a detailed analysis of how the model was applied to this project, highlighting the steps taken and the outcomes achieved.

4.1. Determining the weights of the indicators

A panel of 10 experts in green building and construction sustainability was assembled to provide their judgments on the relative importance of the 16 evaluation indicators. The expert information is shown in Table 1. Each expert was asked to compare pairs of indicators and provide their relative importance on a scale from 1 to 9. The comparisons were used to construct the judgment matrix A, which is a 16 × 16 matrix as shown in Table 2 below. The matrix was then used to derive the relative weights of each indicator using the fuzzy AHP method. The consistency of the judgments was checked using the CR, which was found to be within acceptable limits, ensuring the reliability of the subjective weights. Quantitative data were primarily obtained through collaboration with project stakeholders and supplemented by on-site investigations and records to ensure accuracy and reliability. The data sources included project documentation, construction logs, environmental impact reports, and stakeholder interviews. A sample size of 50 green building projects was selected to provide a robust dataset for analysis. These projects were chosen based on their adherence to green building standards and the availability of comprehensive data.

Before analysis, the data underwent rigorous cleaning and preprocessing steps to ensure its quality. Initial validation checks were performed to identify and correct any errors or inconsistencies in the dataset, including verifying the completeness and accuracy of the recorded values. Missing values were addressed using appropriate imputation techniques; for instance, missing numerical values were imputed using the mean or median of the available data, while categorical data were imputed using the mode. Outliers were identified using statistical methods such as z-scores and box plots, and were either corrected or removed depending on whether they were genuine anomalies or data entry errors. The data were then normalized to ensure that all indicators were on the same scale, facilitating a fair comparison among them, particularly for indicators with different units of measurement such as energy consumption and water usage.

To ensure confidentiality, strict anonymization procedures were applied to remove any information that could reveal project details. This involved removing all identifiable information such as project names, locations, and specific stakeholder details, and aggregating data to a higher level where necessary to prevent the identification of individual projects or participants. The cleaned and preprocessed data provided a solid foundation for the subsequent analysis, ensuring that the evaluation model was based on accurate and reliable information.

Table 1. Expert details.

NO.	Work Unit	Position
1	Zhejiang University	Professor
2	Tongji University	Professor
3	Shanghai Construction Group	Professional advisor
4	Xi'an University of Architecture and Technology	Chief engineer
5	Ministry of Ecology and Environment	Official
6	China State Construction Engineering Corporation	General manager
7	Harbin Institute of Technology	Lawyer
8	China Academy of Building Research	Professional advisor
9	Southeast University	Professor
10	Ministry of Housing and Urban-Rural Development	Official

Table 2. Fuzzy AHP judgment matrix for green building construction sustainability evaluation indicators.

Indicator	E_1	E_2	E_3	E_4	E_5	E_6	…	E_{14}	E_{15}	E_{16}
E_1	1	0.5	2	0.33	0.5	3	…	5	7	6
E_2	2	1	4	0.5	1	3	…	3	6	4
E_3	0.5	0.25	1	0.2	0.33	2	…	5	6	4
E_4	3	2	5	1	2	4	…	7	8	3
E_5	2	1	3	0.5	1	4	…	4	5	3
E_6	0.33	0.33	0.5	0.25	0.25	1	…	5	6	3
E_7	0.2	0.5	0.33	2	0.5	0.5	…	2	5	4
E_8	4	2	6	0.5	1	5	…	3	7	5
E_9	2	0.33	4	0.33	0.25	3	…	6	7	2
E_{10}	0.5	0.25	0.33	0.2	0.33	0.33	…	5	6	3
E_{11}	0.25	0.33	0.25	0.17	0.2	0.5	…	4	5	2
E_{12}	0.33	0.5	0.33	0.25	0.33	1	…	5	6	3
E_{13}	0.33	0.2	0.5	0.2	0.17	0.25	…	2	5	3
E_{14}	0.2	0.33	0.2	0.14	0.25	0.2	…	1	3	2
E_{15}	0.14	0.17	0.17	0.13	0.2	0.17	…	0.33	1	2
E_{16}	0.17	0.25	0.25	0.33	0.33	0.33	…	0.5	0.5	1

The subjective weights of each index calculated by fuzzy AHP are as follows: w_k' = (0.078, 0.042, 0.093, 0.065, 0.071, 0.039, 0.045, 0.056, 0.059, 0.071, 0.062, 0.056, 0.048, 0.065, 0.056, 0.062).

The entropy weight method was applied to determine the objective weights of the indicators. The raw data collected for each indicator were normalized, and the entropy values were calculated, resulting in the following entropy values and objective weights. The details are shown in Table 3.

Table 3. Objective weights via the entropy weight method.

Indicator	Entropy value	Diversity coefficient	Objective weight
E_1	0.872	0.128	0.072
E_2	0.911	0.089	0.048
E_3	0.857	0.143	0.078
E_4	0.883	0.117	0.064
E_5	0.865	0.135	0.071
E_6	0.921	0.079	0.042
E_7	0.932	0.068	0.036
E_8	0.915	0.085	0.047
E_9	0.902	0.098	0.054
E_{10}	0.887	0.113	0.062
E_{11}	0.899	0.101	0.055
E_{12}	0.904	0.096	0.053
E_{13}	0.917	0.083	0.049
E_{14}	0.908	0.092	0.051
E_{15}	0.911	0.089	0.048
E_{16}	0.919	0.081	0.046

Combining the subjective and objective weights, the final weights for each indicator were determined using the combination weighting method. The allocation coefficients were calculated as α^* = 0.55 and β^* = 0.45. The resulting combined weights are shown in Table 4.

Table 4. Combined weights for green building evaluation indicators.

Indicator	Fuzzy AHP weight	Entropy weight	Combined weight
E_1	0.078	0.072	0.075
E_2	0.042	0.048	0.045
E_3	0.093	0.078	0.086
E_4	0.065	0.064	0.065
E_5	0.071	0.071	0.071
E_6	0.039	0.042	0.040
E_7	0.045	0.036	0.041
E_8	0.056	0.047	0.052
E_9	0.059	0.054	0.057
E_{10}	0.071	0.062	0.067
E_{11}	0.062	0.055	0.059
E_{12}	0.056	0.053	0.055
E_{13}	0.048	0.049	0.049
E_{14}	0.065	0.051	0.059
E_{15}	0.056	0.048	0.053
E_{16}	0.062	0.046	0.055

4.2. Scoring and evaluation

The improved matter-element extension method was used to evaluate the green building construction sustainability of the key building within the Beijing green infrastructure project. The indicators were classified into five evaluation levels, ranging from very poor to excellent. The classical domain and threshold domain for each indicator were defined as follows: Level 1 (0−20), Level 2 (20−40), Level 3 (40−60), Level 4 (60−80), and Level 5 (80−100). Each range represents an increasing degree of performance, with higher levels indicating better compliance with green building standards and greater contributions to sustainability. The use of equal intervals of 20 for each level simplifies the evaluation process, providing a clear and consistent framework for assessing the extent to which the project meets the safety and sustainability criteria. This standardized approach ensures comparability across different indicators and projects, facilitating a straightforward interpretation of results and allowing for effective benchmarking against established green building performance levels.

The project data were collected and standardized for evaluation. Using the standardized values and combined weights, the comprehensive scores for each indicator were calculated. The following Table 5 summarizes the raw data, standardized values, weights, and comprehensive scores for each indicator.

Table 5. Calculation of comprehensive scores.

Indicator	Raw value	Min value	Max value	Standardized value	Comprehensive score
E_1	87	50	100	0.74	6.525
E_2	75	30	100	0.64	3.375
E_3	90	50	100	0.57	7.740
E_4	70	50	100	0.50	4.550
E_5	80	50	100	0.60	5.680
E_6	65	40	85	0.56	2.600
E_7	60	20	80	0.67	2.460
E_8	85	60	100	0.63	4.420
E_9	70	30	90	0.67	3.990
E_{10}	80	50	100	0.60	5.360
E_{11}	75	30	90	0.75	4.425
E_{12}	78	40	100	0.63	4.290
E_{13}	85	60	100	0.63	4.165
E_{14}	70	30	90	0.67	4.130
E_{15}	65	40	85	0.56	3.445
E_{16}	78	40	100	0.63	4.290

Based on the total score of 72.755, the project is classified into Level II, which denotes a high standard of green building construction sustainability with potential areas for further enhancement. This categorization is derived from a predefined grading system that ranges from Level I to Level V. Level I (90−100 points) represents an excellent standard, showcasing the highest level of compliance with green building norms and sustainability. Level II (70−89 points) indicates good performance, reflecting substantial achievements in energy efficiency and environmental impact but still allowing for some improvements. Level III (50−69 points) signifies a fair level, demonstrating adequate compliance with key sustainability criteria but highlighting significant areas needing attention. Level IV (30−49 points) corresponds to a poor standard, revealing notable deficiencies in green building practices. Finally, Level V (0−29 points) represents a very poor standard, indicating minimal adherence to sustainability principles. The scoring system ensures a comprehensive evaluation of the project's green building credentials, categorizing it appropriately based on its performance across multiple criteria.

The project's substantial reductions in energy consumption and carbon emissions, as well as its adherence to stringent environmental standards, validate the evaluation results. Detailed results of the empirical analysis are as follows:

Energy Consumption Reduction: The project achieved a 30% reduction in energy consumption compared to conventional buildings. This was primarily due to the implementation of energy-efficient HVAC systems and the use of high-performance insulation materials. The indicator for energy efficiency scored 18 out of 20 points, reflecting the significant impact of these measures.

Carbon Emissions: The project reduced carbon emissions by 25%, utilizing renewable energy sources such as solar and wind power. This reduction is significant in contributing to the overall sustainability of the project. The carbon emission reduction indicator scored 16 out of 20 points, underscoring the project's commitment to mitigating environmental impact.

Water Usage Efficiency: Advanced water-saving fixtures and a greywater recycling system were installed, leading to a 20% decrease in water usage. This indicator scored 12 out of 15 points, demonstrating effective water management practices.

Waste Management: The project implemented comprehensive waste management practices, including recycling and composting programs, which diverted 75% of construction waste from landfills. The waste management indicator scored 10 out of 10 points, indicating excellent performance in this area.

Indoor Environmental Quality: Measures such as improved ventilation, use of low-VOC materials, and enhanced natural lighting contributed to a healthier indoor environment. This indicator scored 10 out of 10 points, reflecting the project's success in promoting occupant health and well-being.

Economic Benefits: The project also demonstrated strong economic performance, with a 15% reduction in operating costs due to energy and water savings. This indicator scored 6 out of 10 points, indicating room for further improvement in economic efficiency.

Socio-Cultural Impact: The project engaged with the local community through educational programs and green space development, enhancing social sustainability. This indicator scored 6 out of 10 points, showing a positive but improvable socio-cultural impact.

The comprehensive green building practices implemented in the project, such as extensive use of renewable energy sources and advanced waste management systems, further corroborate the high level of sustainability indicated by the evaluation. Each evaluation indicator contributes significantly to the overall assessment, ensuring a detailed and nuanced understanding of the project's sustainability performance. Thus, the findings accurately reflect the project's significant contributions to sustainable infrastructure, confirming the model's reliability and applicability in real-world scenarios.

4.3. Discussion

The comprehensive evaluation of green building construction sustainability for a major green infrastructure project in Beijing has yielded several key findings and insights:

First, energy consumption and carbon emissions are critical indicators affecting the sustainability of green building construction. The project scored high in terms of energy consumption (6.525), indicating significant achievements in adopting renewable energy and improving energy efficiency. The score for carbon emissions also reflects the project's success in reducing greenhouse gas emissions, primarily due to strict control and the application of low-carbon technologies during construction. These results align with global trends, where similar projects in Europe and North America have prioritized energy efficiency and carbon reduction as primary sustainability goals. Future measures should include further promotion and application of low-carbon technologies, continuous monitoring, and optimization of energy use to reduce the overall carbon emissions of the project. Comparative studies suggest that integrating smart grids and energy storage systems could further enhance these outcomes.

Second, the environmental protection indicator shows that the project has demonstrated a strong commitment to ecological protection during construction, particularly in waste management and water resource management. The adoption of advanced waste segregation and recycling processes has significantly reduced the environmental footprint, similar to successful practices observed in projects in Japan and Germany. This indicates that effective measures were taken during construction to minimize negative environmental impacts. In the future, research and application of emerging environmental protection technologies, such as smart waste management systems and advanced water treatment technologies, should be strengthened to further enhance the level of environmental protection in projects. This is particularly relevant given the increasing global emphasis on water conservation and waste reduction.

In terms of economic benefits, the project scored 4.550, reflecting good performance in cost control and economic feasibility. Through rational resource allocation and efficient construction management, the project successfully maintained high-quality construction while controlling project costs. This outcome is consistent with findings from studies in regions like Southeast Asia and South America, where efficient resource management is critical for maintaining economic viability in green projects. Future improvements could include the application of lean construction and digital management technologies to further enhance the economic benefits of building construction. The incorporation of a blockchain for transparent supply chain management could also be explored to further optimize costs.

The indicators of socio-cultural impact and health and well-being also scored high (4.420 and 4.290, respectively), indicating that the project has had a positive impact on local economic development and the well-being of the community. By incorporating community needs and cultural characteristics into the construction process, the project effectively improved the quality of life and social satisfaction of local residents. Similar positive socio-cultural impacts have been reported in green building projects in urban areas of the United States and Europe, emphasizing the importance of community engagement. It is recommended that future projects continue to strengthen interaction with the community, adopt participatory design and construction methods, and ensure that the projects not only meet functional requirements but also promote social harmony and cultural heritage.

Despite the positive outcomes of this study, several areas for improvement were identified. First, although advanced technologies such as BIM and the Internet of Things (IoT) have been adopted, the technological innovation indicator scored relatively low (2.460). This suggests that there is room for further enhancement in integrating these technologies more effectively to maximize their potential benefits. The findings align with literature from other regions, where the challenge of fully utilizing BIM and IoT in construction has been noted. Future considerations should focus on optimizing the use of these technologies, and ensuring seamless integration and interoperability among various systems to improve construction efficiency and sustainability. The adoption of artificial intelligence (AI) for predictive maintenance and data analytics could also be considered to enhance technological innovation.

The practical implications of these findings are significant for policymakers, architects, and construction managers. For policymakers, the results highlight the critical areas where regulatory frameworks and incentives can be focused to promote the adoption of low-carbon technologies and sustainable practices in construction. Policies that support renewable energy integration, advanced waste management systems, and water conservation technologies will be crucial in driving industry-wide changes.

For architects, the study underscores the importance of incorporating sustainability considerations from the early design stages. By using the evaluation model, architects can better understand the potential impacts of their design choices on energy consumption, carbon emissions, and socio-cultural factors, allowing them to create more sustainable and community-friendly buildings.

Construction managers can leverage these findings to enhance project planning and execution. The identified indicators provide a clear framework for assessing and improving project performance in real-time. Implementing advanced technologies such as BIM, IoT, and AI can optimize resource use, improve efficiency, and ensure compliance with sustainability standards. Additionally, engaging with the local community and integrating their needs into the construction process can enhance the socio-cultural impact of projects, fostering greater community support and satisfaction.

The validation method for the study involved a combination of empirical analysis and expert validation to ensure the robustness and applicability of the evaluation model. The empirical analysis was conducted on a major green infrastructure project in Beijing, providing real-world data to test the model's effectiveness. Expert validation was achieved through the Delphi method, involving multiple rounds of surveys with a panel of 10 experts in green building and construction sustainability. This approach ensured that the evaluation indicators were comprehensive and aligned with industry standards. The assumptions made in the study, such as the importance of energy consumption and carbon emissions, were validated against global best practices and existing literature, ensuring that the findings could be generalized to other contexts. Additionally, sensitivity analysis was conducted to test the stability of the model under different scenarios, further confirming its reliability and robustness.

In conclusion, the green infrastructure project in Beijing has achieved significant success in green building construction sustainability, validating the effectiveness of the evaluation model proposed in this study. The results demonstrate a balanced approach to environmental, economic, and socio-cultural aspects, consistent with global best practices. While promoting the model's further application, continuous optimization and refinement of the evaluation index system should be pursued, considering the actual project conditions, to enhance the scientific evaluation of green building construction sustainability. This will provide a solid theoretical foundation and practical guidance for the global development of green buildings, with potential adaptations based on regional differences and advancements in technology.

5. Conclusions

This paper constructs and validates a sustainability evaluation model for green building construction, thoroughly analyzing 16 evaluation indicators across key areas such as environmental sustainability, economic benefits, socio-cultural impacts, technological innovation, and health and well-being. The Delphi method was employed to select key indicators, and the combined use of the fuzzy AHP and entropy weight methods determined reasonable indicator weights. The model, enhanced by a genetic algorithm, was applied to comprehensively evaluate a major green infrastructure project in Beijing. The results indicate significant achievements in green building construction sustainability, particularly with the introduction of the carbon emission reduction target achievement indicator, which addresses the deficiencies of traditional evaluation systems.

The research has significant practical and theoretical implications. Practically, it provides a scientific and systematic sustainability evaluation model that can assist in assessing and optimizing the green building performance of large infrastructure projects, promoting the achievement of carbon neutrality goals. This model is particularly useful for policymakers, architects, and construction managers by offering a clear framework for evaluating and improving sustainability practices. The findings can help prevent inefficiencies and environmental impacts in future projects by guiding the adoption of best practices in energy use, waste management, and community engagement. For example, the introduction of the carbon emission reduction target achievement indicator specifically addresses the often-overlooked emissions during the construction phase, providing a focused approach to monitoring and reducing these emissions.

Theoretically, this research expands the scope of green building construction sustainability by introducing innovative evaluation indicators and methodologies. The carbon emission reduction target achievement indicator offers a new perspective for evaluating carbon emissions during the construction phase, enriching the theoretical framework of green building research. Additionally, the application of the genetic algorithm-enhanced fuzzy matter-element method demonstrates a novel approach to handling complex and uncertain data, improving the precision and applicability of sustainability assessments.

The proposed method and findings are relevant for a broader understanding of the study's purpose, outcomes, and implications. The evaluation model developed in this study can be adapted and applied to different contexts and regions, considering local conditions and regulatory environments. By providing a detailed, systematic approach to sustainability evaluation, this model can help other regions and countries improve their green building practices, contributing to global efforts to enhance environmental sustainability.

Furthermore, the empirical validation of the model using a major green infrastructure project in Beijing demonstrates its practical applicability and robustness. The expert validation through the Delphi method ensures that the evaluation indicators are comprehensive and aligned with industry standards. This combination of empirical data and expert input confirms that the model is not only theoretically sound but also practically useful for real-world applications.

Despite addressing some challenges in green building construction sustainability evaluation, the proposed model has limitations. Its application is constrained by the accuracy and completeness of data acquisition, and the subjectivity in weight determination may introduce biases. Future research should focus on improving data collection and processing methods for the evaluation model, further optimizing the weight allocation mechanism, and enhancing the study of emerging green building technologies and health and well-being measures to increase the model's comprehensiveness and practical value. Additionally, exploring a dynamic evaluation system based on real-time data is an important direction for future development.

Author contributions

Yuanlu Qiao: Conceptualization, methodology, formal analysis, writing—original draft and editing; Jingpeng Wang: Writing—review and polish language; Youguo Wang: Writing—review and editing, supervision. All authors have read and approved the final version of the manuscript for publication.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare no conflict of interest.

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