

Article

Prioritization of Sustainability Factors in Highway Construction Using the AHP Method

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Sustainability has emerged as a central consideration in modern construction engineering, particularly in large-scale infrastructure projects such as highways. This study focuses on identifying and analyzing the critical factors that influence the sustainability of highway construction projects from a construction engineering perspective. The research utilizes the Analytic Hierarchy Process (AHP), a structured multi-criteria decision-making technique, to assess the relative importance of grouped sustainability indicators in relation to project owner priorities. These include technical performance, construction duration, quality standards, and constructability. The analysis is structured around the three core pillars of sustainability—environmental, economic, and social and integrates them with engineering-focused evaluation criteria. The findings reveal that specific factors such as Energy use noise emissions during construction, long-term maintenance costs, and the degree of social integration have significant implications for sustainable construction outcomes. These factors not only affect the environmental footprint of highway projects but also influence cost efficiency, operational resilience, and social acceptance throughout the project life cycle. Based on the results, the study presents a set of engineering-oriented recommendations to enhance sustainability performance. These include adopting environmentally sensitive construction techniques, optimizing resource use and life cycle costs, engaging relevant stakeholders early in the planning and design phases, and implementing integrated project delivery (IPD) and sustainable construction management practices. By integrating these recommendations, highway construction projects can achieve a more balanced and sustainable performance across technical, environmental, and social dimensions, thereby aligning with national and international sustainable infrastructure goals.

KEYWORDS

**Highway Construction;
Analytic Hierarchy
Process; Sustainability
Development.**

HIGHLIGHTS

- Developed an integrated AHP-based framework to prioritize sustainability indicators in highway construction.
- Categorized 43 sustainability indicators into environmental, economic, and social dimensions.
- Collected and analyzed expert responses using a bilingual questionnaire in the Egyptian highway sector.
- Found economic sustainability factors (30.8%) to be more influential than environmental (20.5%) and social (8%) factors.
- Provided actionable recommendations to enhance sustainable construction practices in developing countries.

1. Introduction

The construction industry is inherently complex and distinguished by its fragmented structure, multidisciplinary operations, and dynamic project environments. It consistently encounters persistent challenges such as budget overruns, schedule delays, excessive material waste, and the intensive consumption of non-renewable natural resources. A particularly concerning statistic is that the construction sector is responsible for approximately 40% of

global raw material consumption solely for new construction activities [1]. Furthermore, the industry is widely recognized as one of the leading contributors to environmental degradation, emitting significant amounts of greenhouse gases and generating considerable construction and demolition waste. Within this context, highway construction projects are especially resource-intensive, demanding large quantities of energy, raw materials, and

logistical inputs throughout their planning, execution, and maintenance phases. These projects often result in considerable environmental losses, including ecosystem disruption, increased carbon footprint, and depletion of natural aggregates. The scale and complexity of highway infrastructure further amplify the industry's sustainability challenges, underscoring the urgent need to adopt more sustainable construction engineering practices and resource-efficient methodologies to mitigate long-term environmental impacts [2]. Value Engineering is “a systematic and organized approach to providing the necessary functions in a project at the lowest cost without compromising quality, reliability, performance, or safety” [3]. It focuses on function analysis and creative problem-solving to optimize value by balancing performance, cost, and other project constraints. Originally developed by Lawrence Miles at General Electric in the 1940s, VE has since evolved into a widely applied methodology in construction, manufacturing, and service industries. Sustainable Development is defined by the Brundtland Commission as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [4]. It is commonly framed through the “triple bottom line,” which integrates three interconnected pillars: environmental protection, social equity, and economic viability.

Traditionally, highway construction projects have primarily been evaluated and managed based on three fundamental criteria: cost, time, and quality. These parameters have long served as the dominant performance indicators in construction planning and decision-making processes. However, this conventional approach has often overlooked broader considerations related to environmental sustainability, social equity, and long-term human needs. As a result, critical factors such as ecological degradation, resource depletion, community displacement, and health-related externalities have received insufficient attention in both the design and execution phases of highway infrastructure projects. With the growing global emphasis on sustainable development, there is an increasing recognition that economic efficiency and technical performance must be balanced with environmental protection and social responsibility. Consequently, the integration of sustainability principles into highway construction has become imperative to ensure that projects meet not only immediate functional requirements but also contribute positively to ecological preservation and community well-being over the long term [5].

From a historical perspective, the development of highway infrastructure has been predominantly guided by three core performance metrics—cost-efficiency, adherence to project timelines, and the attainment of specified quality standards. This traditional emphasis shaped project objectives, contractual frameworks, and construction methodologies for decades, but it also explains why broader societal and environmental considerations were often overlooked. Limited attention was given to the long-term needs of end-users, the ecological consequences of construction

activities, and the risks associated with failing to uphold social responsibility standards. As a result, unsustainable practices such as habitat disruption, excessive resource consumption, and insufficient stakeholder engagement became common. In response, there is now a growing consensus within the construction engineering field that future highway development must adopt a more holistic framework—one that integrates economic, environmental, and social dimensions into every phase of the project lifecycle [6]. The initial steps in developing a sustainable highway involve reuse planning and the responsible utilization of available on-site resources. However, quantifying the environmental and economic benefits of using recycled materials in construction remains challenging without comparable and quantitative analytical approaches [5]. While many transportation authority's worldwide have adopted sustainable alternatives as standard practice, further efforts are necessary to meet the growing demand for resources from all sources [7].

Conventional construction practices and management approaches often lack the capacity to effectively address the complex and evolving demands of sustainability within the built environment. These traditional frameworks are typically oriented toward short-term project goals such as budget adherence and timely delivery while failing to adequately incorporate long-term environmental and social considerations. In contrast, sustainability in construction represents a comprehensive and multidimensional paradigm that encompasses a wide range of interrelated elements, each with distinct yet complementary objectives. Achieving meaningful progress toward sustainability requires a fundamental shift in how construction activities are planned, executed, and evaluated. Specifically, it involves reducing the ecological footprint of construction operations through resource efficiency, emissions control, and waste minimization while simultaneously aligning with the broader goals of the triple bottom line: environmental stewardship, social equity, and economic viability. The integration of these pillars into construction engineering practice is essential for promoting resilient infrastructure that serves both present and future generations [8].

2. Literature Review

Over the past few decades, extensive research has been conducted to examine the challenges and opportunities associated with sustainable construction. This growing body of literature reflects the increasing global recognition of the construction sector's critical role in advancing sustainable development goals. As one of the largest and most resource-intensive industries worldwide, the building and construction sector possesses substantial potential to drive transformative change by addressing the interrelated economic, environmental, and social impacts of its operations.

By confronting issues such as high energy consumption, material waste, greenhouse gas emissions, and limited stakeholder engagement, the industry can transition toward more responsible and sustainable practices.

Effectively leveraging this potential requires the integration of innovative design strategies, green technologies, and policy frameworks that promote lifecycle thinking and long-term value creation. Consequently, the construction sector is positioned not only as a contributor to environmental degradation but also as a pivotal agent in achieving global sustainability objectives [1]. The rapid expansion of the construction industry has been closely associated with significant environmental impacts, primarily due to the intensive consumption of natural resources such as energy, water, and raw materials and the large-scale generation of construction and demolition waste [2]. As a result, sustainable development has gained increasing prominence within the construction sector, prompting researchers, policymakers, and industry professionals to seek strategies that balance infrastructure growth with environmental preservation [6].

In emerging economies, such as Egypt, accelerated urbanization continues to drive the demand for large-scale infrastructure projects, particularly in the highway construction sector. While such projects are essential to supporting national economic development and improving transportation networks, they often impose considerable environmental burdens. These include increased waste production, depletion of natural resources, and elevated levels of pollution. Therefore, incorporating sustainability principles into the planning and execution of highway projects in developing countries has become imperative to mitigate adverse environmental effects while sustaining economic growth.

Sustainable highway development plays a vital role in supporting community well-being and stimulating economic growth, while simultaneously promoting environmental protection and the conservation of natural resources. To achieve these objectives, it is essential to incorporate sustainability-oriented project characteristics and ensure their consistent application throughout the entire project life cycle from planning and design to construction, operation, and eventual decommissioning. A comprehensive assessment of the highway project's life cycle is fundamental to achieving sustainability goals. This requires an integrated evaluation framework that considers environmental impacts (such as emissions, resource use, and ecosystem disruption), economic factors (including cost efficiency, lifecycle value, and maintenance), and social dimensions (such as community accessibility, health, and safety). By addressing these three pillars environmental, economic, and social throughout the project's life cycle, highway infrastructure can be designed and implemented in a manner that balances development needs with long-term sustainability outcomes [3]–[5].

Value Engineering (VE) is a systematic and function-oriented methodology aimed at optimizing project value by balancing the diverse priorities and expectations of various stakeholders. It enables organizations to achieve

their functional and performance objectives using the least possible expenditure of resources, without compromising quality or efficiency [10]. VE has proven to be particularly valuable in construction projects where cost-effectiveness, functional performance, and stakeholder satisfaction must be simultaneously addressed.

There are two principal approaches to implementing VE: proactive and reactive. The proactive approach is integrated early in the project life cycle, particularly during the design phase, where multiple design alternatives are explored. This enables the selection of the most cost-effective and functionally sound solution before construction begins. Conversely, the reactive approach is applied after initial designs have been developed. In this case, value-improvement proposals are generated by involving external contributors such as contractors, design engineers, and consultants, who evaluate existing designs to identify more economical or efficient alternatives. Both approaches aim to enhance value by improving function while reducing unnecessary costs.

A process called value engineering (VE) is used to balance the many values that various stakeholders have put. It makes it possible for a company to achieve its objectives with the least amount of resources [6]. There are two approaches to VE: proactive and reactive. Proactive idea collection begins with the design, where all possible options are considered, and the most economical one is chosen. Reactive methods gather affordable options by having other people, such as contractors and designer engineers, evaluate the designs [7]. To develop material choices for highway building projects that maximize sustainability indicators and other owner requirements, the study intends to provide a workable framework for value engineering hybrid with AHP.

Sustainable development is defined as the process of fulfilling present societal, economic, and environmental needs without compromising the ability of future generations to meet their own requirements. In the context of construction and infrastructure development, this principle emphasizes the responsible use of resources, long-term planning, and the integration of environmentally conscious strategies to ensure intergenerational equity and resilience [8]. Conventional buildings have a high energy consumption rate during the building phase. The construction sector is a major global consumer of natural resources and a significant contributor to environmental degradation. It is estimated that the industry accounts for approximately 40% of global energy consumption, 12% of the world's clean water usage, and 30% of total global resource extraction. Beyond the construction phase, the operation and maintenance of buildings and infrastructure assets further exacerbate environmental impacts through indirect contributions to greenhouse gas emissions, which are projected to constitute up to 40% of total global emissions.

Looking ahead, the environmental burden of the construction sector is expected to intensify, particularly in rapidly developing regions. By 2030, it is anticipated that Asian countries alone will contribute approximately 30% of these global construction-related emissions. These projections highlight the urgent need for sustainable construction practices, energy-efficient design, and responsible resource management to mitigate long-term environmental consequences[9].

The challenges associated with sustainable development—particularly those related to energy consumption, material usage, and environmental degradation—are fundamentally engineering challenges that require technical innovation and systemic solutions. While substantial research has been conducted across various industrial sectors to address aspects of sustainability, much of the existing literature tends to focus on individual components of the sustainability triad (economic, environmental, or social), rather than adopting an integrated and holistic approach

In the context of construction and infrastructure development, this fragmented perspective limits the effectiveness of sustainability strategies. Several studies have primarily emphasized social dimensions, such as labor conditions, community impact, and stakeholder engagement, while underrepresenting the interconnectedness of environmental and economic considerations. This underscores the need for comprehensive, interdisciplinary models in construction engineering that simultaneously address all three pillars of sustainability—ensuring balanced development outcomes that are environmentally sound, economically viable, and socially responsible. [10]–[20]. The environmental aspects are as in [12], [21]–[29]. The economic aspects are as in [30]–[34]. Sustainable construction means creating and operating a healthy environment based on ecological design and resource efficiency [35]. The concept of sustainable construction encompasses the integration of social, economic, and environmental development goals within the built environment, aiming to generate long-term value for both current and future communities. It reflects a comprehensive approach that not only seeks to reduce the ecological footprint of construction activities but also promotes social equity and economic resilience throughout infrastructure development.

To operationalize these objectives, Sustainable Construction Principles have been established to serve as guiding frameworks across all project phases—from early planning and design through to execution and operation. These principles emphasize life cycle thinking, encouraging the adoption of environmentally responsible materials, energy-efficient technologies, and socially inclusive practices that collectively enhance the overall sustainability performance of construction projects. By applying these principles throughout the entire project life cycle, construction professionals can ensure that

sustainability is embedded into the core of decision-making and project delivery processes [35]. The sustainability indicators adopted in this study were derived through a comprehensive review of relevant literature [40,41]. These indicators were selected based on their relevance to highway construction projects and their alignment with stakeholder priorities across the project life cycle. As illustrated in Table (1), the key sustainability indicators reflect the perspectives of various project stakeholders, including owners, engineers, contractors, and community representatives.

For analytical clarity, the indicators were systematically categorized into three main dimensions of sustainability: environmental sustainability, socio-economic sustainability, and economic sustainability. This classification enables a structured evaluation of sustainability performance by capturing the multifaceted impacts of construction activities—from ecological considerations and community well-being to cost-effectiveness and long-term resource efficiency.

Over the past two decades, extensive research has been conducted to explore the incorporation of sustainable materials in highway construction, with the objective of reducing environmental impacts and promoting resource efficiency. One prominent approach involves the reuse of selected waste materials including construction and demolition debris, glass waste, scrap rubber, fly ash, granulated blast furnace slag (GBFS), colliery spoils, polyethylene terephthalate (PET), mine tailings, reclaimed shingles, aluminum dross, and bio-based oils.

These materials have been evaluated either individually or in combination, serving as partial or complete substitutes for conventional construction materials in various stages of roadway construction and rehabilitation. Studies have investigated their applicability in base and sub-base layers, asphalt mixtures, and concrete components. The integration of such alternative materials not only contributes to waste reduction and landfill diversion but also enhances the sustainability performance of highway infrastructure by lowering energy use, minimizing resource depletion, and potentially reducing overall construction costs [36]–[44].

In a real-world case study conducted in a mountainous region, the highway alignment was automatically optimized using advanced design and simulation tools. This optimization process resulted in measurable sustainability benefits, including a 3.6% reduction in carbon dioxide (CO₂) emissions and a 3.1% decrease in land consumption. These improvements were achieved by minimizing earthwork requirements and aligning the roadway with the natural topography, thereby reducing environmental disturbances and material usage. The study highlights the potential of intelligent design approaches in enhancing the environmental performance of highway infrastructure, particularly in ecologically sensitive or

topographically challenging areas [45]. To support decision-makers—such as project managers, engineers, and transportation agencies—in advancing sustainable practices across the life cycle of highway projects, a sustainability index tailored to Egyptian highway infrastructure has been developed. This index serves as a structured framework to guide sustainable design, construction, operation, and maintenance processes in alignment with local environmental, economic, and social priorities. Despite growing efforts to integrate sustainability principles into highway design and construction, a number of scholars and industry practitioners' express skepticism toward the concept of "sustainable highways." They argue that the term remains inherently paradoxical, given the substantial consumption of non-renewable resources and the intensive material demands typically associated with large-scale roadway

infrastructure.

This critical perspective highlights a fundamental challenge in the field: while sustainability frameworks and rating systems provide valuable guidance, their practical implementation often falls short of achieving tangible environmental improvements. Therefore, it is essential not only to adopt sustainability models but also to continuously monitor, evaluate, and refine the environmental performance of highway projects throughout their life cycles. Bridging the gap between theoretical sustainability and real-world outcomes requires a dynamic and evidence-based approach that aligns design intent with measurable environmental impact [46]. However, when carefully considering the triple principles, social and economic benefits demonstrate that highways are a vital part of the infrastructure for society in any country [21].

Table 1. Highway construction sustainability indexes criteria`s

Index	Factor with codes					Reference s
Environmental	Energy use (E1)	Renewable energy (E2)	Water consumption (E3)	Recycling water (E4)	Waste Management (E5)	[47]–[50]
	Material Recycle/ Reuse (E6)	Land Use for Temporary Site Facilities (E7)	Impact on biodiversity (E8)	Air Pollution (E9)	Water Pollution (E10)	
	Noise Pollution (E11)					
Economic	Initial cost (C1)	Maintenance cost (C2)	Operational Cost (C3)	Job Creation (C4)	Long term Savings (C5)	[50], [51]
	Equitable Income (C6)	Local Resources (C7)		Employment creation (C8)		
Social	Construction Site Safety (S1)	Local Community Safety (S2)	Employee Wellbeing (S3)	Employee Training and Development (S4)	Employee Satisfaction and Retention (S5)	[47], [50], [52], [53]
	Impact on Local Community (S6)	Social Responsibility (S7)	Innovation Practices (S8)	Effective Management Practices (S9)	Social and cultural life (S10)	
	Social homogeneity and cohesion (S11)	Integration diversity sense of place (S12)	Communication and participation (S13)	Social Justice and Equity (S14)	Social amenity (S15)	
	Social security (S16)	Social Capital and well being (S17)	Access to goods (S18)	Service and Employment (S19)	Education (S20)	
	Training (S21)	Democracy (S22)	Engaged Governance (S23)	System for citizen Engagement (S24)		

A number of studies have proposed the systematic integration of sustainable practices into highway projects through scientifically grounded methodologies. In

response to this need, a structured model has been developed and applied in both the construction and maintenance phases of roadway infrastructure. This model extends beyond the concept of green buildings to encompass a broader framework that addresses highway sustainability and incorporates environmentally

responsible practices, often referred to as "green activities."

The model provides a comprehensive approach to embedding sustainability throughout the project life cycle, including material selection, energy use, waste management, and long-term operational efficiency. By institutionalizing these practices, the model aims to standardize and promote the adoption of sustainability as a core component of roadway engineering and management [46]. The conventional processes employed in highway construction can be significantly enhanced through the integration of core sustainable development principles. By embedding best practices in environmental management—such as minimizing ecological disturbance, optimizing resource use, and controlling emissions—into the early stages of road planning and throughout the construction phase, the vision of sustainable highways becomes more attainable.

This approach transforms traditional highway development by shifting the focus from purely technical and economic considerations to a more holistic framework that balances infrastructure performance with environmental stewardship and long-term societal benefit. As a result, sustainability becomes a guiding principle rather than an afterthought in modern roadway engineering [54]. The project's sustainability can be assessed using the Penarafan Hijau JKR (pH JKR) tool [55].

Despite the growing global emphasis on sustainable infrastructure, there remains a noticeable gap in the literature regarding the state of sustainability practices in Egypt's highway construction sector. Addressing this gap, the present study aims to develop a structured approach for evaluating sustainability criteria alongside other owner priorities in highway construction projects through the application of the Analytical Hierarchy Process (AHP). By systematically assessing and assigning weights to various sustainability factors, the research seeks to determine their relative influence on project decision-making and performance. Furthermore, the study examines the key barriers hindering the implementation of sustainability strategies within the Egyptian construction industry, particularly those related to environmental considerations. The findings are intended to provide a context-specific framework that supports informed decision-making, promotes sustainable practices, and enhances the integration of sustainability principles into highway construction in Egypt.

3. Methodology

The research methodology followed a multi-stage approach, as illustrated in Figure 1, to systematically identify and prioritize sustainability-related criteria alongside other owner-defined project considerations. The first stage involved conducting an extensive literature review to extract and categorize sustainability criteria under the three fundamental pillars: environmental, social, and economic. Based on the findings, a bilingual

questionnaire (Arabic and English) was developed, comprising both qualitative and quantitative components, to solicit expert opinions on the relative importance of these sustainability indicators as well as other relevant project criteria. The data collected during this phase were analyzed using both descriptive and inferential statistical methods to identify the most critical criteria influencing sustainable highway development.

In the second stage, the Analytic Hierarchy Process (AHP) was employed to further analyze and prioritize the shortlisted sustainability indicators and owner-related criteria, which included construction time, performance, quality, and constructability. The AHP methodology was applied in two steps: first, to determine the relative weights of the main sustainability and owner criteria using pairwise comparisons; and second, to derive the specific weights of individual sub-indicators under each main criterion. The study was conducted within the Eastern and Western Delta regions of Egypt, and the final results reflect the weighted significance of each factor, providing a structured foundation for evaluating and implementing sustainability in regional highway projects.

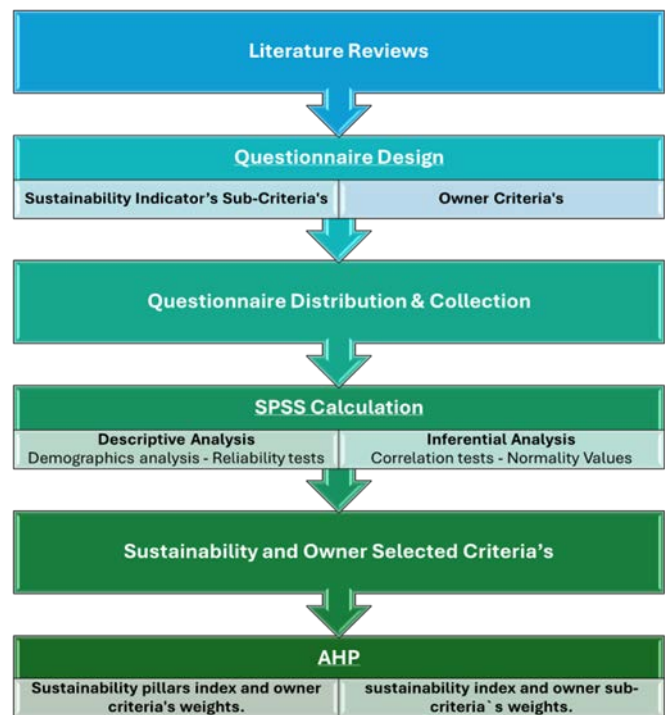


Figure 1. Research methodology chart

4. Material And METHODS

A. Questionnaire collection

Data for the survey and accompanying questionnaire were collected from 123 respondents, out of a total of 160 invitations distributed to targeted participants. This yielded a response rate of 76.87%, which is considered acceptable for statistical analysis in similar research contexts [55]. To facilitate accessibility and ease of response, the questionnaire was disseminated electronically via Microsoft Forms. Before conducting the main analytical procedures, the collected data underwent

a series of preliminary statistical tests using SPSS software. These included demographic analysis to understand the background of the respondents, as well as tests for reliability (to assess internal consistency), normality (to verify distribution assumptions), and correlation (to examine relationships among variables). These steps ensured the robustness and validity of the data prior to applying the Analytic Hierarchy Process (AHP) in subsequent stages of the study. For determining the sample size for questionnaire, we applied Cochran's formula for unknown Population: $N = Z^2 \left(\frac{P(1-P)}{e^2} \right)$. At confidence level 90% $Z = 1.64$, $e = 7.5\%$, $P = .4$ sample size is 122 [56].

a. Questionnaire results analysis

i. Demographics analysis

The demographic profile of the respondents was analyzed to assess their academic background and professional experience in the construction sector. As illustrated in Figures 2 and 3, the data reflect varying levels of education and years of experience, indicating a diverse and knowledgeable sample relevant to the study context. Additionally, Figure 4 presents the types of organizations to which the respondents belong, along with their professional roles within those entities. Furthermore, the annual value of organizational work, expressed in Egyptian Pounds (million/year), is summarized in Table (2). This indicator provides insight into the scale and financial capacity of the participating organizations, further validating the relevance and representativeness of the surveyed sample for examining sustainability and decision-making practices in Egyptian highway construction projects.

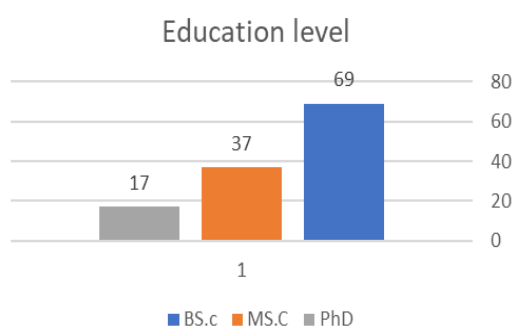


Figure 2. Response education level and experience's years

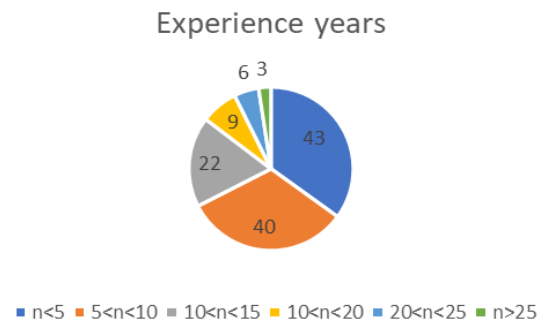


Figure 3. Response experience's years organization and job title

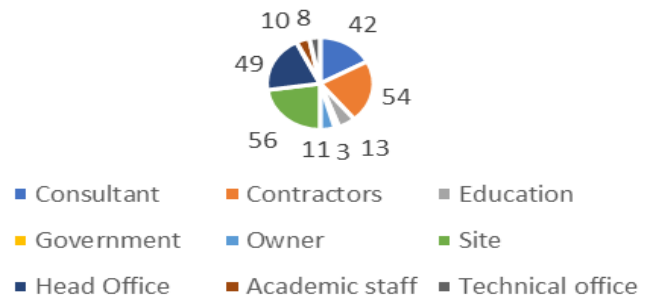


Figure 4. organization and job title

Table 2. Annual organization work per year (million)

Organization work value per year (million)	Unknown	<10	10-50	50-100	100-500	>500
Number	68	12	11	8	6	18

i. Statistical analysis

A reliability test was conducted to assess the internal consistency and stability of the questionnaire responses using Cronbach's Alpha coefficient. As presented in Table (3), the overall Cronbach's Alpha for the complete set of 43 sustainability-related indicators was calculated at 0.89, which is classified as an excellent level of reliability, indicating high internal consistency across all items. When analyzed by category, the environmental sustainability indicators (11 factors) yielded a Cronbach's Alpha of 0.81, reflecting a good level of reliability. The economic sustainability indicators (8 factors) recorded an Alpha value of 0.775, which is also considered good. Notably, the social sustainability indicators (24 factors) achieved a Cronbach's Alpha of 0.82, representing an excellent level of internal consistency. These results confirm that the instrument used in the study is statistically reliable and suitable for further analysis and interpretation in the context of evaluating sustainability criteria in highway construction projects [57]. To ensure the reliability of the results, the correlation process was rigorously applied to assess the strength and significance of relationships between sustainability criteria and owner priorities within the AHP framework. Correlation coefficients were calculated to identify consistent

patterns, and statistical significance testing was performed to confirm that these associations were not the result of random variation. This systematic validation process not only reinforces the robustness of the weighting results but also directly supports the study's objective of developing a reliable, evidence-based framework for integrating sustainability into highway construction decision-making in Egypt.

A normality done by Kolmogorov-Smirnov and Shapiro-Wilk tests, showed that ($p < 0.001$), indicating significance, and the value of Statistic was between (1) and (-1), which represented normally distributed data [58]. According to the Spearman correlation theory, all factors at a confidence level between 95% and 99%. The correlated factors were categorized into three environmental factors, four economic factors, and three social factors, totaling 10 factors. The strength of the inter-correlation between the factors was assessed using a correlation matrix (R-matrix), which represented the Pearson correlation coefficient between all pairs of factors.

Table 4. Sustainability indicators correlated factors

Environmental				Social				Economic				
	E1	E9	E11		S1	S10	S13		C1	C2	C3	C5
E8	1.00	0.58	0.332	S1	1.00	0.63	0.872	C1	1.00	0.550	0.62	0.88
E9	0.58	1.00	0.739	S10	0.633	1.00	0.772	C2	0.55	1.00	0.64	0.88
E11	0.33	0.7	1.00	S13	0.872	0.77	1.000	C3	0.62	0.640	1.00	0.51
								C5	0.88	0.886	0.51	1.00

B. AHP RESULTS

As part of the study's methodology, relevant data were gathered regarding sustainability indicators and owner-defined criteria in the context of highway construction projects, with the aim of identifying the most critical influencing factors. Through an extensive literature review, a wide array of concepts and insights were compiled to support the selection of suitable material additives for different highway pavement layers. In alignment with the Analytic Hierarchy Process (AHP) framework, the Evaluation Phase was implemented to assign relative weights to grouped factors. This phase followed the Creativity Phase, during which a variety of potential solutions and materials were proposed. AHP facilitated a structured and objective evaluation of these ideas by comparing them against a defined set of criteria and sub-criteria.

The matrix was inspected to test the relationships between factors, and none of the correlation coefficients were less than 0.3 or greater than 0.9, as shown in Table (4).

Table 3. Reliability statistics for sustainability index

Index	Economic	Environmental	Social	All
Cronbach's	0.775	0.81	0.82	0.89
N of Items	8	11	24	43

The AHP methodology was applied in two sequential stages: First, pairwise comparisons were conducted to determine the relative weights of the main sustainability pillars (environmental, economic, and social) and other owner requirements, including construction time, performance, quality, and constructability.

Second, the process was repeated to calculate the weights for the sub-factors under each sustainability indicator category. A 9-point Saaty scale, as shown in Table (5), was employed to carry out the pairwise comparisons, ensuring consistency and rigor in the judgment process. This systematic approach allowed for a transparent and evidence-based prioritization of sustainability criteria, supporting informed decision-making in highway construction planning.

Table 5. Scale for conduct pairwise comparisons

Value	Equally important	Weak importance	Strong importance	Very strong	Absolute importance	Intermediate levels
Relevance	1	3	5	7	9	2,4,6,8

according to [59]. The pairwise comparison matrix was constructed based on the geometric mean of the responses

provided by multiple decision-makers, each of whom was assigned equal decision-making authority to ensure an

unbiased and balanced assessment process.

To derive the final weights for each criterion, the weight vector was calculated for each comparison matrix. An approximation method using the arithmetic mean was then applied to aggregate individual judgments and compute the final normalized weights. This methodological approach ensures that the assigned weights reflect a rational consensus among experts while maintaining consistency within the AHP framework. [60].

According to the results of the Analytic Hierarchy Process (AHP), the calculated Consistency Index (CI) was 0.03719, with a maximum eigenvalue ($\lambda_{\max}$) of 7.2231. The Consistency Ratio (CR) was determined to be 0.02817, which falls well below the acceptable threshold of 0.10, indicating a high level of consistency in the judgment matrix. Additionally, the Index of Inconsistency Ratio (IIR) was found to be

1.32, and the overall consistency level of the matrix was 3%, further confirming the reliability and coherence of the pairwise comparisons.

In the second stage of AHP application, the method was extended to evaluate the sub-criteria associated with each main indicator, both within the sustainability dimensions and the owner-required criteria. The results of the sub-criteria analyses are presented in Table (6) and Table (7). The final assigned weights for all sub-criteria—derived from both sustainability indicators and owner priorities—are shown in Table (8) and Table (9). Notably, the aggregated weight of the sustainability-related indicators amounted to 53.7%, which reflects a significant emphasis on sustainability considerations in the context of Egyptian highway construction. This result underscores the increasing national awareness and prioritization of sustainable development practices in infrastructure planning and delivery.

Table 6. Sustainability factors weight

Indicator	Environmental			Economical				Social		
W %	100%			100%				100%		
Factor	E1	E9	E11	C1	C2	C3	C5	S1	S10	S13
W %	15	10	75	32.2	45.3	7.5	15	60	35.7	4.3
CIR	0.01283			0.0415				0.0201		
IIR	0.58			0.9				0.58		
CI	0.00744			0.03735				0.0117		
$\lambda_{\max}$	3.01488			4.112				3.0234		
Consistency	5%			6%				7%		

Table 7. owner criteria factors weight

Indicator	Owner criteria's			
W %	100%			
Factor	Performance	Constr. Time	Quality	Constructability
W %	40	15.5	30.7	13.8
CIR	0.045048			
IIR	0.9			
CI	0.04054			
$\lambda_{\max}$	4.1216			
Consistency	8%			

The weights of the sub-criteria derived from both the sustainability indicators and the owner-defined criteria are presented in Table (8) and Table (9). These tables provide a detailed breakdown of the relative importance of each sub-factor, as determined through the AHP methodology.

It is particularly noteworthy that the cumulative weight of the sustainability indicators amounts to 59.3%, surpassing the combined weight of the other owner-related criteria. This outcome highlights a clear emphasis on sustainability in the prioritization process, reflecting an

increasing national commitment in Egypt toward integrating environmental, social, and economic considerations within highway construction projects. Such prioritization demonstrates the growing recognition of sustainable infrastructure as a strategic objective in national development planning

Table 8. Sustainability sub-criteria factors weight

Indicator	Environmental			Economic				Social			
W %	20.5			30.8				8			
Factor	E1	E9	E11	C1	C2	C3	C5	S1	S10	S21	
W %	4.6	2.9	13	8.5	15	3.3	4	4	2.5	1.5	

Table 9. owner sub-criteria factors weight

Owner criteria's			
40.7			
Performance	Constr. time	Quality	Constructability
13	9	15	3.7

5. Research results and discussion

Based on the adopted methodology which applies the Analytic Hierarchy Process (AHP) to systematically determine the relative importance of grouped factors specific weights were assigned to both sustainability indicators and owner-defined criteria within the context of highway construction projects. For the sustainability dimensions, the AHP results revealed that the economic pillar was the most influential, receiving a weight of 30.8%, followed by the environmental pillar at 20.5%, and the social pillar at 8.0%. These values reflect the practical prioritization of economic efficiency in infrastructure development, while also recognizing the significance of environmental protection and social considerations.

With regard to the owner's performance criteria, the assigned weights were as follows: performance (13%), quality (15%), construction time (9%), and constructability (3.7%). These results indicate that achieving optimal performance and ensuring quality are viewed as more critical than reducing construction duration or enhancing ease of execution. This distribution of weights provides valuable insight into the relative priorities guiding sustainable highway construction in the study context and serves as a decision-support tool for stakeholders seeking to align project objectives with sustainability goals. A detailed analysis of the environmental, economic, and social pillars revealed the specific sub-factors and their corresponding weights, as derived through the AHP methodology.

Within the environmental pillar, the most influential factor was the Energy use, receiving a weight of 4.6%, followed by Noise Pollution at 2.9%, and Air Pollution at 13%. These results underscore the critical importance

placed on preserving biodiversity in highway construction projects, compared to other environmental concerns. In the economic pillar, Maintenance Cost emerged as the most significant factor with a weight of 8.5%, highlighting the growing emphasis on long-term operational efficiency and cost control. Initial Cost was also a considerable factor at 15%, whereas Long-term Savings and Operational Cost were assigned lower weights of 3.3% and 4%, respectively. Regarding the social pillar, Construction Site Safety was the highest-ranked factor, with a weight of 4 %, followed by Social and cultural life at 2.5%, and Training at 1.5 %. These findings reflect a moderate level of importance given to social engagement and integration in infrastructure planning, though generally less prioritized than economic and environmental considerations. This detailed weighting analysis offers critical insight into the value structure underlying sustainability assessment in highway construction projects, supporting more informed and balanced decision-making.

6. Conclusion

Achieving sustainability in highway construction projects necessitates an integrated and balanced approach that holistically addresses the environmental, economic, and social dimensions. Key environmental priorities include mitigating biodiversity loss, as well as reducing noise and air pollution, which are essential for minimizing the ecological footprint of infrastructure development. From an economic standpoint, emphasis should be placed on optimizing maintenance costs and accounting for long-term financial savings, both of which contribute to lifecycle cost efficiency. On the social front, fostering effective communication and stakeholder participation is vital to ensuring community engagement and social acceptance of highway projects. In relation to owner-defined criteria, the Performance factor was assigned the highest relative weight (13%), highlighting its critical role in achieving functional and operational goals. Quality (15%), Construction Time (9%), and Constructability (3.7%) were also recognized as influential components, reflecting their collective contribution to the overall success and sustainability of project outcomes.

The findings underscore the necessity of adopting a multidimensional evaluation framework in decision-making processes related to highway construction projects. Such a framework should integrate not only traditional performance and cost metrics, but also comprehensive sustainability indicators that embody broader environmental, economic, and social values. To enhance the environmental sustainability, it is essential to develop and implement targeted strategies aimed at mitigating the impact on biodiversity, including habitat restoration initiatives and ecological conservation programs. In addition, effective measures should be employed to minimize noise and air pollution throughout both the construction and operational phases of the project.

From an economic sustainability perspective, priority

should be given to optimizing maintenance costs through the use of durable materials, efficient design practices, and robust construction methods. Incorporating life-cycle cost analysis is also vital to evaluate the long-term financial implications and identify opportunities for cost savings across the project lifespan. In terms of social sustainability, it is imperative to promote active stakeholder engagement across all project stages, ensuring that community perspectives are adequately represented. Furthermore, social cohesion and cultural heritage can be preserved by integrating local input and cultural considerations into the design and implementation processes. Regarding the owner-related criteria, the study highlights the importance of aligning project outcomes with defined performance objectives, ensuring the highway fulfills its intended functions and user requirements. Moreover, effective management of construction time, quality standards, and constructability is crucial for achieving timely project delivery, operational efficiency, and long-term value. Collectively, these strategic directions contribute to a more sustainable, resilient, and socially inclusive approach to highway infrastructure development.

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