INTERNATIONAL JOURNAL OF SUSTAINABLE CONSTRUCTION ENGINEERING AND TECHNOLOGY
ISSN: 2180-3242 e-ISSN: 2600-7959

IJSCET

Vol. 16 No. 3 (2025) 47-60
https://publisher.uthm.edu.my/ojs/index.php/ijscet

Development of a Framework for Assessing the Sustainable Index for Maintaining Low-Volume Rural Roads in India

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DOI: https://doi.org/10.30880/ijscet.2025.16.03.005

Article Info

Received: 17 March 2025
Accepted: 20 September 2025
Available online: 5 December 2025

Keywords

Low-volume roads, rural road maintenance, sustainability indicators, sustainability rating tool, analytical hierarchy process, rural roads assessment

Abstract

In India, low-volume rural roads (LVRRS) make up 75% of the road network and provide significant economic and social benefits. However, these advantages risk declining over time due to insufficient maintenance. The continuous deterioration of these roads leads to substantial time losses, reduced agricultural productivity, longer travel times, increased vehicle operating expenses, and a higher likelihood of accidents. To ensure sustainability, it is essential to have a thorough understanding of the interplay between social needs, economic factors, environmental concerns, and material conditions. Therefore, this study employs a quadruple-bottom-line (QBL) approach to support the development of a rural road maintenance framework focused on sustainability. Importantly, merely transferring indicators and criteria from one country's road assessment framework to another is unsuitable due to geographical variations. This study seeks to establish sustainable indicators for assessing the maintenance effectiveness of LVRRS. Experts from diverse road agencies will be involved to ensure that the indicators accurately reflect the current conditions of specific regions. This effort necessitates incorporating multiple decision-makers' perspectives and considering various dimensions and criteria to meet the defined objectives. To create a comprehensive framework, a reliable weighting structure has been proposed to emphasize the significance of different elements related to the sustainable upkeep of rural roads. An Analytical Hierarchy Process (AHP) is utilized to assign weights within hierarchical structures across various domains. To demonstrate the practical application of this tool, four typical maintenance tasks on the major rural roads in the Warangal district have been examined as case studies. The selected projects were in or around Hanamkonda, Warangal, and Kazipet in Telangana. These projects were determined to be unsustainable out of the nine roads that were assessed using the RRSIM framework. Two other road projects were given two RRSIM stars, while the revitalization, overlay, and maintenance projects each received one.

1. Introduction

Rural roads are a vital part of the country's transportation system because they connect villages, towns, and remote areas across a range of geographical terrains. These roads facilitate socioeconomic development, provide access to essential services, support agricultural activities, and connect rural communities to larger road networks. In 2000, the Pradhan Mantri Gram Sadak Yojana, or PMGSY, was launched with the goal of improving the standard of living in rural areas by providing better access to markets, healthcare, education, and other essentials. Road construction and upgrades, connection prioritization, funding, implementing agencies, monitoring, and evaluation are important program components. The construction of rural roads has steadily increased since PMGSY was implemented. The upkeep of these roads, however, has received less attention. Proper maintenance is essential for the roads to remain in good condition without negatively impacting users and community development. The allocation of funds plays a significant role in road maintenance. The situation in India, characterized by poor maintenance of rural roads, is mainly due to insufficient funding. Therefore, a holistic approach is needed to address the challenges in the maintenance of rural roadways. Hence, this study focuses on the concept of sustainable maintenance for rural roads. This approach ensures the integration of sustainability factors, which include social, economic, environmental, and material considerations, paving the way for a quadruple bottom-line strategy. This methodology integrates these factors into decision-making processes, leading to more informed and balanced maintenance strategies.

1.1 Rural Roads and Their Influence on the SDGs

Rural roads play a vital role in achieving more than half of the Sustainable Development Goals (SDGs) and fulfilling the 2030 Agenda for Sustainable Development's pledge to 'leave no one behind.' Even though no individual SDG target focuses explicitly on rural access, its strong linkage with multiple SDGs is clearly evident. The practical and widespread implementation of rural transport significantly contributes to achieving various SDGs:
SDG 1: Reduce Poverty

SDG 2: End Hunger and Ensure Food Security

SDG 3: Promote Health and Well-being

SDG 4: Ensure Access to Quality Education

SDG 5: Strengthen Empowerment of Women in Rural Regions

SDG 6: Improve Access to Clean Water and Sanitation

SDG 8: Foster Inclusive Economic Growth and Employment

SDG 9 and SDG 11: Support Development of Sustainable Infrastructure and Livable Communities

SDG 13: Enhance Climate Resilience and Adaptation in Rural Areas

Although no SDG specifically targets rural access, Indicator 9 and 11 directly addresses this by tracking the proportion of the rural population living within two kilometers of an all-weather road.

2. Literature Review

The literature pertaining to various dimensions of rural road infrastructure, such as the performance index, sustainable maintenance practices, economic and environmental integration, environmental impact and sustainability, life cycle sustainability assessment, and maintenance strategies incorporating carbon footprint considerations, has been critically reviewed. This study is presented in a detailed, scientific, and systematic manner. The sustainability concept was introduced first in 1987 [1]. The Brundtland Commission defined it as the "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." During the latter part of the 1990s [1] and [2] reviewed nine sustainability rating tools for pavement maintenance activities, and those are as follows:

The US Green Building Council developed leadership in Energy and Environmental Design (LEED), and the latest version of the rating tool consists of five modules for evaluating different infrastructure construction [2]. Neighborhood Development (ND) and operations and maintenance modules could be considered for sustainable pavement maintenance among the five modules. The Neighborhood Development module (ND) focuses on projects involving developing or redeveloping new land. The credits are related to paving construction difficulties (including habitat planning and restoration, water bodies, and site disturbance minimization). The operation and maintenance (O+M) Module includes materials related to infrastructure maintenance [3].

INVEST, Greenroads, GreenLITES, I-LAST, BE2ST, STARS, and Green Pave are sustainability rating tools that vary in their focus on pavement maintenance. While INVEST and Green Pave prioritize maintenance indicators, others like GreenLITES and I-LAST include fewer maintenance-related criteria. The above indicators are related to pavement maintenance activities. However, the rating tools fall short in that they place an excessive amount of emphasis on maintenance tasks compared to design and construction costs throughout the transportation infrastructure's life cycle, limiting the ability to quantify sustainability in maintenance tasks [2]. [4] introduced a two-stage approach to identify the most appropriate maintenance activities for various road sections based on factors like priority, road condition, and importance. This method proved to be both time-efficient and cost-effective, requiring only minimal data for implementation [4]. [5] developed a pavement performance index for rural roads using 14 distress parameters identified from expert opinions. They computed PPI using a priority ranking model after normalizing these parameters using the Analytic Hierarchy Process (AHP). Cronbach's alpha was used to assess the reliability scale [5]. [6] and [7] provided a comprehensive approach for integrating technical, economic, and environmental considerations into sustainable pavement management. This methodology comprises assessing maintenance treatments, conducting a comparative analysis, and analyzing sustainability indicators over the pavement life cycle in order to ascertain the benefits and drawbacks of each strategy. These research efforts resulted in the development of a dynamic life cycle assessment (LCA) tool for assessing asphalt pavement designs that incorporate recycling and alternative materials technologies. The purpose of the tool was to reduce the amount of data that the designer needs to input [6, 7].

The maintenance and performance evaluation of India's rural roads have drawn more attention in recent years. A pavement performance index that provides a methodical framework for maintenance prioritization was developed in order to assess rural roads [1, 8]. Their study assessed multiple prioritization strategies and recommended the most effective one for practical application based on criteria like accuracy, time efficiency, and user-friendliness [1, 9]. Sustainability in pavement management has also drawn attention as a result of studies showing how important it is to consider environmental effects when making decisions. In order to enhance sustainable pavement management strategies, [7] and [10] looked into how ecological considerations might be added to pavement treatment optimization. In order to ensure comprehensive and informed decision-making, their research demonstrated the importance of conducting systematic sustainability evaluations using a variety of rating systems [7, 10]. The sustainable management of rural unpaved roads has also received attention. In his discussion of the environmental and economic concerns associated with these road networks, [11] offered management techniques that effectively balance these factors. Additionally, in order to balance agency costs and environmental impacts, [12] proposed a multi-objective optimization strategy for pavement preservation [11, 12].

This integrated approach was further developed by research by [13], [14], and [15] by looking at life cycle scenarios for various pavement technologies. They emphasized the importance of sustainability in urban infrastructure and developed weighted evaluation criteria using Delphi surveys. Their findings demonstrate the significance of expert-driven prioritization strategies for integrating technical, financial, and environmental factors into pavement management systems and for making informed decisions about transportation funding [13, 14, 15]. Furthermore, research has been done on the role of sustainability rating systems such as Greenroads. [16] and [17] evaluated sustainability trends using Greenroads-certified project data, demonstrating how these tools can guide ecologically friendly road practices. Additionally, more thorough assessments are being conducted using advanced frameworks and tools. [18] and [19] combined life cycle cost analysis (LCCA) with building information modeling (BIM) to assess the cost-effectiveness and sustainability of pavement maintenance throughout its lifecycle. These studies proposed a framework for assessing life cycle sustainability with a focus on material selection [16, 17, 18, 19]. To help with the transition to more ecologically friendly material choices, [20] specifically looked at the economic and environmental impacts of using recycled materials in pavement construction. Maintenance planning for low-volume roads has also been addressed by [21] and [22] by developing deterioration and maintenance models especially for these roads. Their efforts support efficient planning while adhering to sustainability objectives, especially when considering developing nations such as Sri Lanka [20, 21, 22]. [23] offered guidance on how local governments can create maintenance and rehabilitation management systems that are in line with sustainable practices. Paik (2018) also included user costs and carbon footprint in road maintenance plans, providing a model that strikes a balance between economic and environmental factors [23, 24].

2.1 Insights Drawn from Earlier Research

The studies collectively highlight the importance of integrating environmental, economic, and technical aspects into pavement management. Emphasis is placed on developing frameworks and tools that can guide sustainable practices, particularly in low-volume and rural road contexts. There is a consistent call for updating existing rating systems and frameworks to address broader sustainability goals, including social and managerial dimensions. This literature review encompasses a range of studies focusing on sustainable pavement management, highlighting the need for comprehensive and integrated approaches to achieve long-term sustainability in infrastructure projects.

The results of the conducted literature review are as follows:

- Prioritization of rural roads for maintenance with sustainable features mainly depends on indicators such as social, economic, environmental, pavement conditions, and materials.
- From the various types of prioritization methods available, AHP is better in approaches than other methods.
- Maintaining rural roads' pavements sustainably requires a comprehensive approach that considers the pavements' entire life cycle, puts preservation above reconstruction, uses recycled materials, uses energy-efficient construction techniques, welcomes innovative designs, and promotes community involvement.
- Implementing these strategies can sustainably maintain rural road networks, ensure longevity, and minimize environmental impact.

3. Research Approach

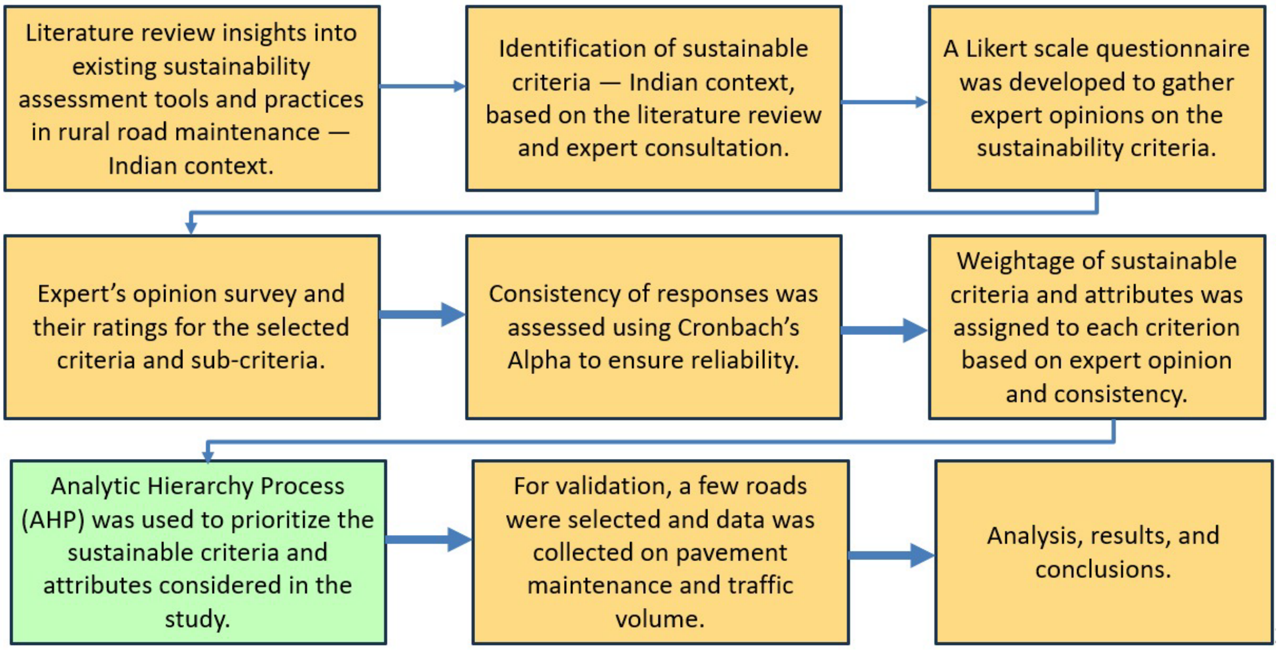

Fig. 1 *Research approach*

The process of creating the Low-Volume Rural Road Sustainability Index (LVRR-SIM), which aims to protect low-volume rural roads, is depicted in Figure 1. This index evaluates the sustainability of low-volume rural roads by integrating economic, material, social, and environmental factors using the Quadruple Bottom Line (QBL) framework. Finding important indicators regarding the importance and urgency of rural road repair involves a review of the literature and an expert survey.

Environmental, economic, social, and material (EESM) factors are the four primary indicators identified in this study. These indicators were created by integrating the results of a literature review with expert viewpoints from academia, road design, construction, and maintenance, and then administering a Likert scale survey. The RRSIM development process consisted of five major steps: identifying rating categories, selecting specific indicators for each category, ranking them, assigning point values to each indicator, and developing certification standards. Eight rating categories were created using the data gathered, allowing for a thorough examination of the factors influencing the importance and urgency of road maintenance. The reliability of the scale was assessed using the Cronbach's Alpha Data Consistency Test.

Additionally, the Analytic Hierarchy Process (AHP), a multi-criteria decision-making method, was employed to evaluate the relative significance of these categories, promoting a systematic comparison of criteria based on their importance. The data collection process and overall research framework are likely illustrated in Figure 1, which shows how the data is organized and applied in this study. This structured methodology aims to assess the relative importance of various criteria in determining the sustainability of low-volume rural road maintenance.

3.1 Establishing Relevant Evaluation Criteria

A wide range of tools have been developed that focus on sustainability. Some agencies have considered pavement as one of their assessment criteria. Only a very few assessment tools have been developed in the field of sustainable pavement practices. The factors are compared and analyzed based on the credibility of each rating system or tool. The criteria for assessing these rating systems vary according to the techniques, practices, climate, region, community, awareness, safety levels, etc.

Table 1 *Pavement maintenance criteria from established assessment frameworks*

Agency	Criteria	Attributes
FHWA	Internal Operations	Internal Sustainability
		Use and Efficiency of Electrical Energy
		Use and Efficiency of Vehicle Fuel
		Reduce, Reuse, and Recycle
		Safety Management
		Environmental Commitments Tracking System
	Maintenance and Operations	Maintenance Management System
		Preservation and Maintenance of Highway
		Infrastructure and Maintenance of Traffic Controlling
		Management Program for Road Weather
		Work Zone Traffic Control
Greenroads	Project Requirements	Energy and Carbon Footprint
		Quality Control
		Prevention of Pollution
		Management of Waste
	Construction Activities	Noise and Glare control
		Asset Management
		Quality Process
		Equipment Fuel Efficiency
		Work zone Air emissions
		Work zone Water Use
		Accelerated Construction
		Communications and Outreach
	Utilities and Cont.	Reduction of Traffic Emissions
		Reduction of Travel Time
	accessibility	Enhancements of Safety
Green LITES	Operational	Project Design Scorecard
		Operations Spreadsheet
	Tactical	Project Solicitation Tool
	Strategic	Regional Sustainability Assessment
		Regional Infrastructure Sustainability Elements
I-LAST	Environmental	Protect, Enhance, or Restore Wildlife and its Habitat
	Transportation	Traffic Operations
	Materials	Materials

Agency	Criteria	Attributes
BE²ST	Environmental	Energy Consumption Global Warming Potential Water Consumption In-situ Recycling Rate
	Economic	Life Cycle Cost
	Voluntary	Energy-efficient lighting and communication Safety Improvement
INVEST	Energy	Installation of road energy systems
	Noise Management	Temporary Noise measures during construction
	Resource Management	Materials with greater environmental benefits Reuse contaminated fill material.
	Road Design	Coordinate works with other public infrastructure Incorporating future maintenance requirements
	Urban Design	Aesthetic views and community infrastructure
	Water and Waterway Mgmt..	Use of non-potable water Incorporate water-sensitive road design.
STARS	Plan	Integrated Process Cost Effectiveness
	Project	Cost Effective Analysis
STAR	Economic	Fiscal burden
	Poverty and Social	Employment Safety
	Environmental	Climate resilience
	Risk to sustainability	Design and evaluation of risk Operation risk
GreenPave	Pavement Technologies	Noise mitigation Cool Pavements
	Materials and Resources	Recycled content Undisturbed pavement structure Local materials Construction quality
	Energy and Atmosphere	Reduced energy Consumption GHG emission reduction Pollution reduction
	Innovation & Design Process	Innovations in design and Exemplary process

Nine existing rating tools that consider pavement maintenance activities as part of their sustainability assessment of a project are selected. Their criteria and sub-criteria related to the pavement are compared and reviewed, as shown in Table 1. A comparison of the tools helped identify the deficiencies in their selection of criteria. Identifying the most notable sustainable criteria, and their corresponding sub-criteria considering the specific local context, climate conditions, culture, maintenance techniques, and practices that persist in India, are determined. A panel of experts was selected to rate their opinions on the identified list of criteria and sub-criteria. Based on the results, the requirements were refined, and further analysis was carried out.

3.2 Expert's Opinion Survey

A survey using a Likert scale was used in this investigation. Based on their pertinent experience in pavement design, construction, and maintenance, experts were carefully chosen. Academicians, research researchers, decision-makers, engineers, and locals made up the expert panel; each had extensive training, credentials, experience, and understanding of the topic. One of the most popular techniques for gathering data was a questionnaire survey, which was used to acquire expert opinions and viewpoints. The parameters used to create the questionnaire were initially taken from a comparison of rating instruments that were already in use. Experts then rated these factors. Based on their feedback, the criteria were refined as shown in Table 2, and final weights for each criterion and sub-criterion were determined for integration into the assessment tool.

Table 2 *List of Identified criteria and sub-criteria*

Code	Sustainability Criteria	Attributes
Mn	Management	Team Structure and Collaboration Financial Planning Quality Assurance Crisis Management Maintenance Planning Project Documentation Worksite Coordination Staff Training
Te	Technique	Maintenance Methods Material Manufacturing Damage Assessment Interruption and Restoration Standardized Procedures
Ma	Material	Quality Accreditation Use of Local Resources Material Storage Management Recycled Materials Alternative Resource Materials
En	Energy and Water	Energy Use in Construction Energy Use in Transportation Energy Use in Traffic Flow Water Usage Efficient Lighting
Ev	Environment	Air Pollution Control Noise Management Nighttime Operations Environmental Protection Solid and Liquid Waste Management
S	Safety	Traffic Management Construction Site Safety Highway and Roadside Safety Pedestrian and Cyclist Safety Drainage Systems Glare Management
C	Community	Road Access for Users Road Access for Infrastructure Cultural Heritage Preservation Community Integration Sustainability Advocacy Stakeholder Participation User Friendliness
I	Innovation	Innovative Solutions Sustainability Coordinator

3.3 Analysis of Survey Data

From the various stages of the survey conducted, a total of 178 responses were collected, and the share of responses from the experts are presented in Table 3.

Table 3 *Expert's category and responses*

S. No.	Category of Experts	Responses collected in numbers	Share of responses to data
1	Engineers	70	39%
2	Academician	40	23%
3	Research Scholars	22	12%
4	Consultants	16	9%
5	Managers	15	9%
6	Others with sound knowledge in this field	15	8%
	Total Number of Responses	178	100%

3.4 Relative Importance Index

The Relative Importance Index (RII), also known as the Weighted Average Method or Importance-Performance Analysis, is a technique used to assess the relative significance of various traits or aspects within a specific context. It ranks elements according to their perceived level of importance and helps identify the key drivers or determinants that significantly influence a particular outcome or choice as shown in Figure 2 and Table 4 displays the calculated RII values for the criterion.

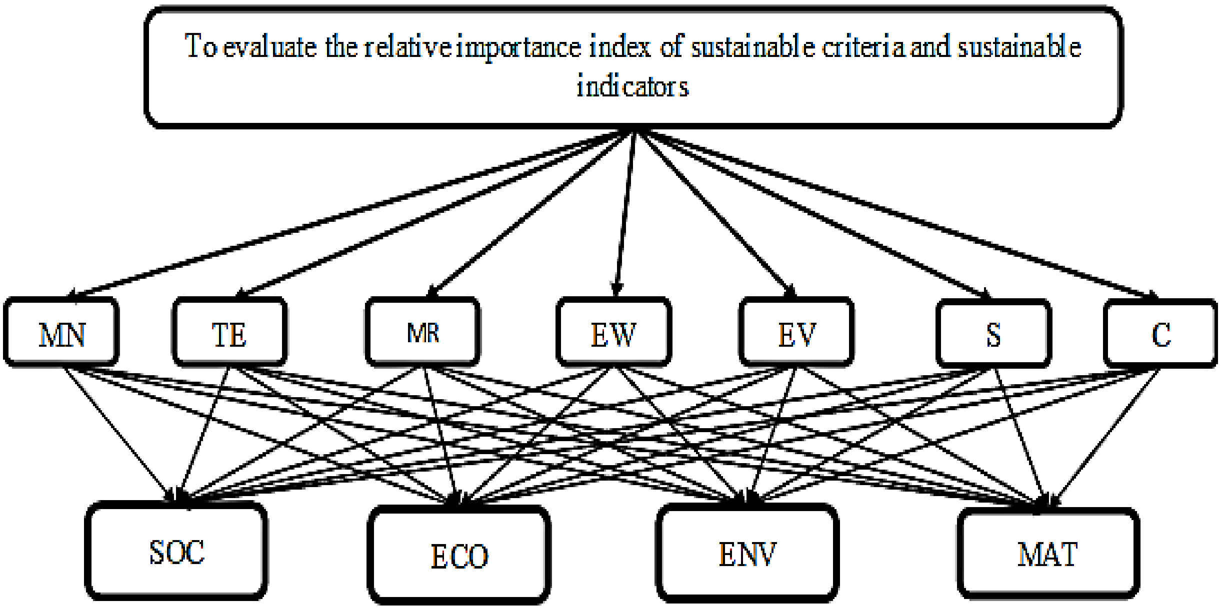

Fig. 2 *Hierarchical structure of Sustainable criteria concerning RRSIM Indicators*

The identified attributes are categorized according to the main criteria, and their relevance of importance concerning the specific context is determined with the help of the relative importance index, which facilitates the comparison of each criterion concerning one another and the main criteria.

Table 4 *RII of the attribute concerning criteria*

Criteria	Attributes	RII
Mn	Mn1	0.723
	Mn2	0.696
	Mn3	0.734
	Mn4	0.683
	Mn5	0.705
	Mn6	0.731
	Mn7	0.713
	Mn8	0.685
Te	Te1	0.710
	Te2	0.716
	Te3	0.680
	Te4	0.688
	Te5	0.706
Mr	Mr1	0.705
	Mr2	0.714
	Mr3	0.693
	Mr4	0.672
	Mr5	0.677
Ew	Ew 1	0.672
	Ew 2	0.680
	Ew 3	0.663
	Ew 4	0.691
	Ew 5	0.685
Ev	Ev 1	0.618
	Ev 2	0.618
	Ev 3	0.647
	Ev 4	0.688
	Ev5	0.652
S	S1	0.704
	S2	0.708
	S3	0.708
	S4	0.659
	S5	0.646
	S6	0.625
C	C1	0.735
	C2	0.725
	C3	0.717
	C4	0.722
	C5	0.719
	C6	0.715
	C7	0.727
I	I1	0.698
	I2	0.692

3.5 Data Consistency Using Cronbach's Alpha

The reliability, or internal consistency, of the scale or questionnaire was evaluated using Cronbach's alpha coefficient, often called Cronbach's alpha. This coefficient measures the degree to which the items of a scale are interconnected and consistently assess the same underlying concept. It evaluates reliability by analyzing the correlation levels among scale items. A higher value of Cronbach's alpha, which falls between 0 and 1, indicates superior internal consistency. A score of 0 represents a lack of internal consistency, implying that the items are unrelated and do not measure the same concept. In contrast, a value of 1 signifies perfect consistency, meaning all items are tightly linked and measure the same construct. The formula for computing Cronbach's alpha is presented in Equation 1 as follows:

$$\alpha = (K / (K - 1)) * (1 - (\Sigma\sigma^2 i / \sigma^2 X)) \quad (1)$$

Where:

α - Cronbach's alpha coefficient.

K - the number of items on the scale.

$\sigma^2 i$ - variance of each item.

$\sigma^2 X$ - variance of the sum of all the items scores.

To assess the internal consistency of the eight evaluation criteria in this study, Cronbach's alpha coefficient was calculated. The reliability analysis results, displayed in Table 5 to 8, demonstrate that all evaluated criteria have Cronbach's alpha values exceeding 0.90. Established statistical standards suggest that alpha values above 0.90 represent excellent reliability. This indicates that the chosen criteria are highly consistent and reliable for the intended analysis, reinforcing the robustness of the data utilized in this research.

Table 5 *Cronbach's alpha coefficient for management and techniques criteria*

Code	Management (α = 0.972)			Criteria Code	Techniques (α = 0.965)		
	Mean of Scale if Item Deleted	Variance of Scale if Item Deleted	Cronbach's Alpha if Item Deleted		Mean of Scale if Item Deleted	Variance of Scale if Item Deleted	Cronbach's Alpha if Item Deleted
Mn 1	24.81	59.708	0.960	Te 1	13.92	18.691	0.932
Mn 2	24.95	59.487	0.965	Te 2	13.75	19.662	0.936
Mn 3	24.76	58.387	0.961	Te 3	14.25	18.230	0.936
Mn 4	24.96	59.125	0.972	Te 4	14.15	17.778	0.931
Mn 5	24.90	57.688	0.963	Te 5	13.95	18.795	0.934
Mn 6	24.77	60.731	0.982	-	-	-	-
Mn 7	24.86	60.228	0.963	-	-	-	-
Mn 8	24.95	56.814	0.962	-	-	-	-

Table 6 *Cronbach's alpha coefficient for environment and materials criteria*

Code	Environment (α = 0.943)			Criteria Code	Materials (α = 0.962)		
	Mean of Scale if Item Deleted	Variance of Scale if Item Deleted	Cronbach's Alpha if Item Deleted		Mean of Scale if Item Deleted	Variance of Scale if Item Deleted	Cronbach's Alpha if Item Deleted
Ev 1	12.99	17.190	0.906	Mr 1	13.80	16.664	0.908
Ev 2	13.32	16.854	0.910	Mr 2	13.76	16.494	0.910
Ev 3	13.18	16.317	0.898	Mr 3	13.86	17.675	0.915
Ev 4	12.97	16.219	0.897	Mr 4	13.97	15.646	0.901
Ev 5	13.15	16.067	0.889	Mr 5	13.94	16.183	0.909

Table 7 *Cronbach's alpha coefficient for energy and water and innovation criteria*

Code	Energy and water (α = 0.921)			Criteria Code	Innovations (α = 0.922)		
	Mean of Scale if Item Deleted	Variance of Scale if Item Deleted	Cronbach's Alpha if Item Deleted		Mean of Scale if Item Deleted	Variance of Scale if Item Deleted	Cronbach's Alpha if Item Deleted
Ew 1	13.56	15.466	0.890	I 1	3.15	1.628	-
Ew 2	13.52	14.959	0.888	I 2	3.28	1.512	-
Ew 3	13.61	15.277	0.899	-	-	-	-
Ew 4	13.47	15.549	0.890	-	-	-	-
Ew 5	13.50	16.098	0.910	-	-	-	-

Table 8 *Cronbach's alpha coefficient for community and safety criteria*

Code	Community (α = 0.950)			Criteria Code	Safety (α = 0.963)		
	Mean of Scale if Item Deleted	Variance of Scale if Item Deleted	Cronbach's Alpha if Item Deleted		Mean of Scale if Item Deleted	Variance of Scale if Item Deleted	Cronbach's Alpha if Item Deleted
C 1	20.96	33.472	0.926	S 1	16.44	30.933	0.927
C 2	21.02	33.352	0.922	S 2	16.42	30.446	0.929
C 3	21.05	33.255	0.925	S 3	16.42	30.883	0.930
C 4	21.09	34.322	0.926	S 4	16.66	28.666	0.927
C 5	21.09	32.996	0.924	S 5	16.73	30.049	0.932
C 6	21.12	33.572	0.927	S 6	16.83	30.115	0.931
C 7	21.01	32.415	0.920	-	-	-	-

3.6 Analytic Hierarchy Process

Thomas L. Saaty [25] developed the AHP, which serves as a structured method for decision-making. Its purpose is to help individuals or groups navigate complex choices by systematically evaluating and comparing multiple criteria and options. AHP organizes these elements into a hierarchical structure for the decision problem: criteria represent the main considerations, sub-criteria denote specific components of each criterion, and alternatives refer to the different options available for making the decision. Among the eight criteria, Energy and Water (EW) received the highest weight at 31.11%, as shown in Figure 3, which considers the Economy indication. Likewise, the Environment, Social, and Materials indicators held the highest weights in Techniques (Te), Community (C), and Materials (Mr) at 30.10%, 32.86%, and 33.90%, respectively.

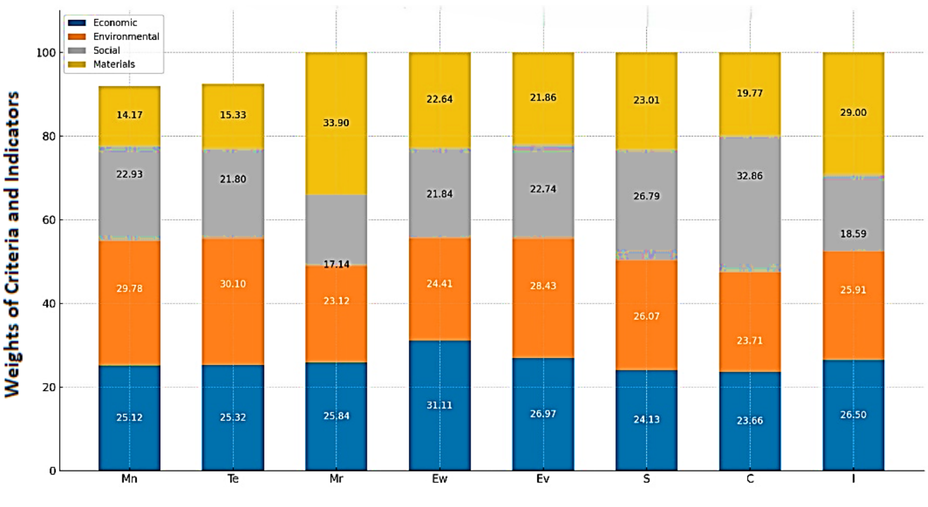

Fig. 3 *Weights of sustainable criteria with respect to sustainable RRSIM indicator*

While considering innovations, the material has gained a weight of 25.84%, indicating that the introduction of marginal and recycled materials has a significant impact on the sustainable maintenance of pavement. Economic indicators play a major part in all criteria, as their weight is comparatively higher in most cases. Since the main lack of maintenance of rural roads is due to limited funds in India, the analysis of responses shows that the economy plays a significant part in the maintenance of rural roads. Next to the economy, an important indicator that should be taken into consideration is the environment since sustainable practices are held to decrease the effects of emissions on the environment, and the results also indicate that the environmental impact is greater. Proper participation of people leads to a positive effect on the development of the community. As per the responses, the impact of social indicators on the community criteria is greater, i.e., it has gained a weightage of 32.86%, as the proper development of the community encourages the stakeholder's investment, too. Notably, the materials indicator incorporated with the Triple-Bottom line (Environmental, Economic, and Social) has also gained a fair weight among the considered indicators.

4. Analysis and Discussion

Using the Analytic Hierarchy Process (AHP) to evaluate sustainability indicators, our study determines the weightings for various criteria, highlighting their importance in affecting decision-making results.

4.1 Economic Indicator

The criterion for energy and water (EW) has the highest weight in this category, at 31.11%. This implies that maximizing resource use and reducing energy and water-related costs are given top priority when making decisions about pavement maintenance, which is in line with the priorities of the residents of the Hanamkonda district.

4.2 Environmental Indicator

The energy and water (EW) criterion, which is an environmental indicator, has the highest weighting in this category (31.11%). This demonstrates how crucial it is to optimize resource use and reduce energy and water-related costs when deciding on pavement maintenance, which represents the priorities of the Hanamkonda district community.

4.3 Social Indicator

Community development-focused social indicators are heavily weighted (26.79%). This highlights the importance of community participation and involvement in pavement repair projects, underscoring the crucial role that social factors play in their effective implementation.

4.4 Material Indicator

With a substantial value of 33.90%, the materials criterion includes innovations like the use of marginal and recycled materials. This highlights the importance of materials in achieving sustainability goals and the influence that sustainable material choices have on pavement maintenance practices.

5. Conclusions

The literature review revealed that very few studies have utilized the Triple Bottom Line (TBL) approach to assess pavement maintenance, highlighting a significant research gap in evaluating sustainability through a multi-dimensional lens. Existing studies primarily focus on pairwise relationships, such as between social and economic or economic and environmental criteria, without fully integrating all three dimensions (financial, environmental, and social) at the same time. Based on expert opinions and the Analytic Hierarchy Process (AHP) analysis, it is concluded that the economic, social, environmental, and material criteria all play significant roles in rural pavement maintenance. Among these, the economic, social, and material aspects stand out and are remarkably high in weight. The economic indicator, particularly regarding energy and water optimization, received the highest weight (31.11%), emphasizing the need for cost-effective, resource-efficient pavement strategies in financially constrained rural areas like the Hanamkonda district of Telangana State. The social indicator, with a weightage of 32.86%, highlights the importance of community development and participation. It demonstrates how inclusive planning increases stakeholder participation and promotes the long-term viability of maintenance initiatives. Utilizing marginal and recycled materials is important, as evidenced by the material indicator's significant weighting of 27.40%. The study concludes that using the QBL framework results in a more comprehensive, balanced, and sustainable approach for rural pavement maintenance. These materials support cost savings and environmental sustainability, making them crucial to sustainable pavement practices. It guarantees that material, social, environmental, and economic factors are all appropriately taken into account. To sum up, adding materials as a fourth pillar to the conventional Triple Bottom Line (TBL) results in a Quadruple Bottom Line (QBL), which makes it possible to assess economic, environmental, social, and material factors more fairly. This integrated approach guarantees decision-making that is comprehensive, sustainable, and tailored to the rural Indian context. This study adds materials as a fourth criterion to the conventional Triple Bottom Line (TBL) approach, transforming it into a Quadruple Bottom Line (QBL) approach that offers a more thorough evaluation of sustainable pavement maintenance.

Acknowledgement

The authors would like to thank the Director and Faculty of Department of Civil Engineering, Transportation Division, National Institute of Technology Warangal, for providing the research facilities.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm their contribution to the paper as follows: ***study conception and design:*** *Raji Reddy Myakala, Shankar Sabavath;* ***data collection:*** *Raji Reddy Myakala;* ***analysis and interpretation of results:*** *Raji Reddy Myakala;* ***draft manuscript preparation:*** *Raji Reddy Myakala, Shankar Sabavath. All authors reviewed the results and approved the final version of the manuscript.*

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