INTEGRATING INDICATOR REVIEW AND SOCIAL NETWORK ANALYSIS FOR SUSTAINABLE PUBLIC INFRASTRUCTURE

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Abstract

The construction sector's current sustainability frameworks are centered around private buildings, with little consideration for public infrastructure. This study reviews global rating frameworks to address these gaps and examines 629 indicators grouped into quantitative and qualitative categories. Social Network Analysis (SNA) is applied to examine the relationships among indicators, identifying 113 distinct indicator groups with a high modularity of 0.975, suggesting weak cohesion and fragmentation among the frameworks. Based on network structure centrality analysis, refined 56 cross-cutting indicators are identified. A three-level hierarchical framework is developed to select and make decisions about indicators for sustainable public infrastructure in India.

Introduction

Infrastructure development plays a significant role in the nation's overall development. Several studies confirm that the infrastructure has an important and beneficial impact on productivity, output, and long-term growth rates (Boix-Cots, Pardo-Bosch and Pujadas, 2023). Beyond economic performance, public infrastructure systems enable the delivery of critical services essential for social justice, public health, economic productivity, and overall quality of life. However, the long-term viability of these services is increasingly threatened by climate change, making sustainability and climate resilience central concerns for infrastructure planning and operation. The operational and structural integrity of the infrastructure is at risk due to the growing frequency and intensity of extreme weather events, including heatwaves, hurricanes, droughts, and floods. (Das, 2025) found that these vulnerabilities lead to service disruptions, economic losses, and increased social inequality in impoverished areas. Sustainability encompasses an assessment of environmental conservation, economic feasibility, and social equity throughout the life cycle of an asset (Sánchez-Silva and Baker, 2024). On the other hand, climate resilience involves planning for, responding to, and recovering from climate-based disruptions while maintaining services (Ferrari, 2020). Incorporating both sustainability and climate resilience into decision-making is critical for developing a sustainable and climate-resilient infrastructure (Cardin, Mijic and Whyte, 2023). This paper presents a conceptual framework that connects short-term development and performance metrics with long-term sustainability and climate resilience goals. The findings aim to assist policymakers, planners, infrastructure agencies, and asset owners by providing a cohesive method for indicator selection, benchmarking, and decision-making in public infrastructure planning and policy formulation. The following section discusses the study's literature background.

Research Background

The rating framework is not homogeneous in assessing environmental, social, and economic aspects across project lifecycles (Khan and Henschel, 2024). Widely used frameworks such as LEED, GRIHA, and IGBC primarily support environmental performance in buildings, focusing on aspects such as energy efficiency, water conservation, and indoor environmental quality in both commercial and residential buildings (Leal *et al.*, 2024), while GRIHA and IGBC focus on integrated habitat assessment and green townships according to the Indian climatic and regulatory context (Kumar, Santara and Banerji, 2020).

However, these frameworks have a drawback in that they primarily focus on private-sector buildings and individual assets with relatively short ownership cycles (Liu *et al.*, 2018). Also, these frameworks do not account for the unique characteristics of public infrastructure, including networked structures (e.g., highways, water grids), multi-decadal lifecycles, multi-level governance coordination, climate risk exposure, and long-term resilience (Liu *et al.*, 2018; Sanad *et al.*, 2025).

There are also infrastructure-centric rating frameworks globally, such as ENVISION, CEEQUAL, Greenroads, SuRe, and the IS Rating tool (Mehraban *et al.*, 2025). However, upon arrival in India, no overarching system exists for rating public infrastructure across environmental, social, economic, and resilience dimensions. Existing rating frameworks, such as GRIHA and IGBC, are for buildings or newly developed highway adaptations and do not provide a comprehensive, integrative, and harmonising system for the entire infrastructure (Kumar, Santara and Banerji, 2020; Jain and Ananda, 2024). Consequently, the existing global rating frameworks, such as ENVISION, CEEQUAL, and IS rating tools, show more bias towards the environmental dimension, and the least concentration on other dimensions of sustainability, such as social and economic (Diaz-Sarachaga *et al.*, 2016).

The significant research gap in developing countries like India is the lack of an integrated, coherent, and consistent framework that integrates environmental, social, economic, and resilience aspects across the lifecycle of public infrastructure. Moreover, developed frameworks in advanced economies fail to include location-specific vulnerabilities, climate risks, or multi-level governance (Diaz-Sarachaga *et al.*, 2016; Kumar, Santara and Banerji, 2020) . Finally, limited use of network analysis to map interdependencies among indicators, stakeholders, and vulnerabilities hinders the transition from isolated assessments to holistic, adaptive decision-making (Khan and Henschel, 2024).

As a result, they fall short in addressing long-term performance, resilience, and adaptability under climate uncertainty, which are central to public infrastructure systems (Sanad *et al.*, 2025). Therefore, there is a lack of harmonisation of sustainability indicators across different global rating systems, such as LEED, BREEAM, and Envision. Although these frameworks include overlapping environmental, social, and economic indicators, they remain fragmented and non-standardised due to their origins in building-scale and private-sector contexts (Mansell *et al.*, 2019). This fragmentation in the industry has negative implications for sustainability assessment in public infrastructure, due to the lack of robust benchmarking, cross-framework comparisons, and comprehensive integration into decision-making (Liu *et al.*, 2018; Mehraban *et al.*, 2025).

To address these challenges, this study combines a systematic review of indicators with Social Network Analysis (SNA) to better understand how sustainability and resilience indicators relate to one another. SNA uses network-based methods to examine patterns, connections, and groupings within complex systems (Rousseau, 2002). In research concerning infrastructure sustainability, SNA elucidates intricate interconnections among indicators, stakeholders, and vulnerabilities, evolving from discrete assessments to comprehensive, adaptive frameworks that identify critical linkages and systemic issues (Khan and Henschel, 2024). While SNA has been applied in construction management research, including supply chain coordination, site operations, and health and safety (Wang, Zhang and Lu, 2018). Its use in structuring sustainability and resilience indicators for public infrastructure remains limited. Therefore, this study adopts a system-oriented perspective to examine public infrastructure as an interconnected network. Studies applying SNA in similar contexts include those that integrate vulnerability indicators with stakeholder objectives in sustainable infrastructure decision-making (Khan and Henschel, 2024). By combining a comprehensive review of sustainability and resilience indicators with Social Network Analysis (SNA), the research aims to reveal how indicators relate to one another, identify gaps and overlaps, and identify which themes dominate current assessment practices. The study further seeks to reorganise these indicators into meaningful clusters that reflect environmental, social, economic, and resilience indicators within the Indian context.

Methodology and Experiment

A four-phase methodology to develop a 3-level hierarchical conceptual framework is proposed, as shown in *Figure 1*.

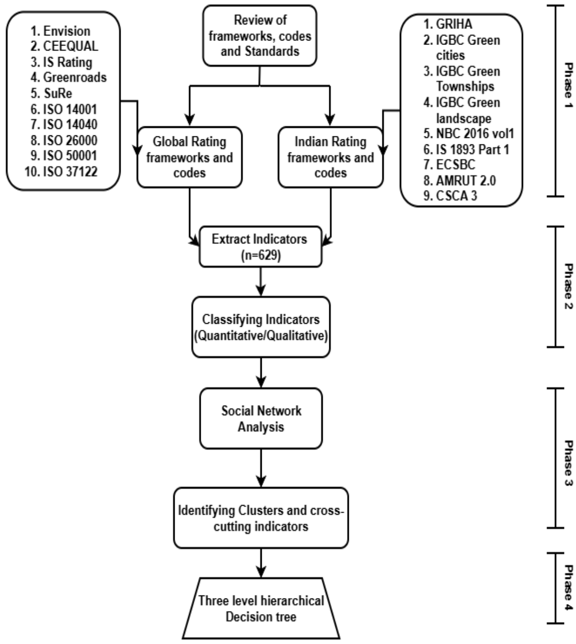

Figure 1: Framework for the development of a 3-level hierarchical decision tree.

Phase 1: Review of Existing Frameworks, Codes, and Standards

A structured review was conducted to identify and analyse sustainability and resilience assessment systems relevant to public infrastructure. This review targets formal rating systems, international standards, national codes, and policy frameworks that define indicator-based assessment criteria. The review covered five major categories:

i. Global sustainability rating systems such as CEEQUAL, SuRe, IS rating, and Greenroads (ICE, 2007; University of Washington, 2011; GIB, 2018; ISCA, 2018; ISI, 2018),
ii. Associated international standards such as ISO 14001:2015, BS EN ISO 14040:2006, ISO 26000; ISO 50001, ISO/CD 37122 (BIS, 2006; ISO, 2011; ISO/TC, 2012),
iii. Indian sustainability rating frameworks such as GRIHA, IGBC (Green township rating, Green cities, and Green landscape rating) (IGBC, 2010, 2013, 2015; TERI, 2010),
iv. Indian building and infrastructure codes such as NBC 2016, ECSBC 2024, & IS 1893 Part 1:2016 (BIS, 2016; IS, 2016; BEE, 2024),
v. Indian policy frameworks, including AMRUT 2.0 and the Climate Smart Cities Assessment Framework 3.0 (MOHUA, 2021, 2022).

Table 1 represents the classification of the Existing Global and Indian frameworks, codes, standards, and policies.

Table 1: Global and Indian sustainability rating systems, codes, and policy instruments

Global rating	Global codes	Indian rating	Indian codes	Indian policies
CEEQUAL	ISO 14001:2015	GRIHA	NBC 2016 VOL 2	AMRUT 2.0
Greenroads	BS EN ISO 14040:2006	IGBC Green Cities	IS 1893 Part 1:2016	Climate Smart Cities Assessment Framework
Envision	ISO 26000	IGBC Green Landscape	ECSBC 2024	
IS Rating	ISO 50001	IGBC Green Townships		
SuRe	ISO/CD 37122			

Frameworks were selected based on their relevance to public infrastructure, including sustainability and climate resilience dimensions, and on the availability of clearly defined indicators.

Phase 2: Indicator Extraction and Classification

In this Phase, sustainability and climate-resilience indicators identified in Phase 1 were extracted and compiled in an Excel database for further analysis. The extracted indicators were then classified into quantitative and qualitative categories to facilitate systematic analysis and standardisation. Indicators were harmonised to remove duplication while retaining their conceptual intent. Quantitative indicators represent measurable variables such as percentages of emission reductions, energy efficiency metrics, and lifecycle costs, while qualitative indicators capture aspects such as stakeholder engagement, community-influenced impact evaluations, and adaptability planning judgments. The quantitative indicators were subsequently used for Social Network Analysis.

Phase 3: Network Construction and Analysis

In this phase, Social Network Analysis (SNA) was used to analyse the relationships among the quantitative sustainability and climate resilience indicators identified in Phase 2. The process involved the following steps.

i. Network construction where each indicator is represented as a node and edges are established based on co-occurrence across multiple rating and assessment frameworks.
ii. Network visualisation and analysis using Gephi, applying the ForceAtlas2 layout to reveal structural patterns.
iii. Community detection or modularity analysis to identify clusters of closely related indicators.
iv. Centrality analysis to identify influential and cross-cutting indicators within the network.

SNA was particularly useful because it enables quantifying inter-indicator relationships, identifying tightly connected clusters, and influential indicators through centrality-based measures. These properties are critical for prioritising indicators that play a bridging or coordinating role in integrated sustainability and resilience decision-making.

Key SNA metrics, such as centrality, density, and modularity, were used to interpret the network structure and identify key structural patterns.

Phase 4: Framework Development

In this phase, the results obtained from SNA were synthesised to develop the conceptual framework. Indicator clusters identified through modularity analysis were interpreted as thematic groupings representing different dimensions of sustainability and climate resilience. The process involved the following steps:

i. Identification of thematic clusters based on community detection results.
ii. Selection of key indicators using centrality measures to identify cross-cutting and influential indicators.
iii. Refinement of indicators based on relevance to the Indian public infrastructure context and removal of redundancy.
iv. Development of a hierarchical structure organising indicators into three levels: indicators, criteria, and requirements.

Based on this process, a conceptual decision framework was established to arrange indicators into coherent thematic hierarchies, thereby facilitating integrated assessment and decision-making for India's sustainable, climate-resilient public infrastructure.

Results and Discussion

Indicator Dataset and Classification

A total of 629 sustainability and climate-resilient indicators were identified from the structured review of global and Indian frameworks, codes, standards, and policy documents relevant to public infrastructure. This comprehensive set of indicators encompasses a broad spectrum of sustainability considerations, including environmental, social, and economic dimensions relevant to infrastructure development.

A total of 387 quantitative and 242 qualitative indicators were identified. To examine the evolution of these frameworks and standards, the temporal distribution of their evolution was studied.

Figure 2 presents a timeline figure illustrating the temporal distribution and contextual diversity of the reviewed global and Indian frameworks, codes, and policy initiatives. The X-axis represents the years from 2000 to 2025, while the Y-axis is classified into five categories: global frameworks, Global codes, Indian rating systems, Indian codes, and Indian policy documents. The graph depicts the evolution of sustainable governance at the global and national levels. Global framework development was dominated in the early to mid-2000s, reflecting the initial international push for sustainability, climate action, and infrastructure evaluation. Global codes became more prominent between 2008 and 2020.

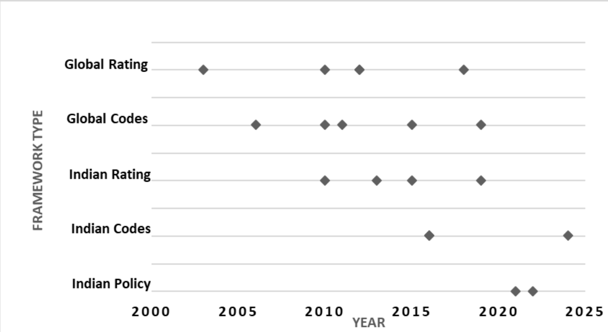

Figure 2: Temporal distribution of global and Indian frameworks, codes, and policy initiatives across different categories.

In the Indian context, rating systems emerged around 2010. This trend indicates the localisation and adaptation of global sustainability concepts into performance-based assessment tools with a specific focus on the building sector, rather than infrastructure systems. Indian codes appear later, primarily after 2015, reflecting a gradual institutionalisation of sustainability principles into formal building regulations and standards. After 2020, the Indian policy, which emphasises the growing role of buildings as key levers for sustainability, decarbonisation, and climate resilience, while broader infrastructure-scale integration remains comparatively limited.

Structural Properties of the Indicator Network

The indicator network was developed by representing each sustainability indicator as a node, with edges indicating co-occurrence across the reviewed frameworks. This strategy enabled systematic mapping of indicator interdependence and redundancy, revealing underlying thematic groupings and highly influential individual indicators. The network was constructed using 387 quantitative indicators identified in phase 2. The indicator network comprises 387 nodes, representing all identified sustainability and climate-resilient indicators. The network exhibits limited connectivity, with an average degree of 1.622, indicating that most indicators are connected to only one or two others. The graph density is very low (0.3%), indicating that only a small fraction of possible connections exists. The diameter of 8 and the average path length of 2.554 indicate efficient local connectivity within the clusters. Multiple connected components exhibited siloed groupings, indicating incomplete integration across the frameworks.

Community Detection and Framework Fragmentation

To understand the internal structure of the indicator network and identify key indicator clusters, community detection was performed using a modularity-based algorithm as discussed in Phase 3. This method enables the identification of clusters of indicators that are more densely connected to each other than to the rest of the network.

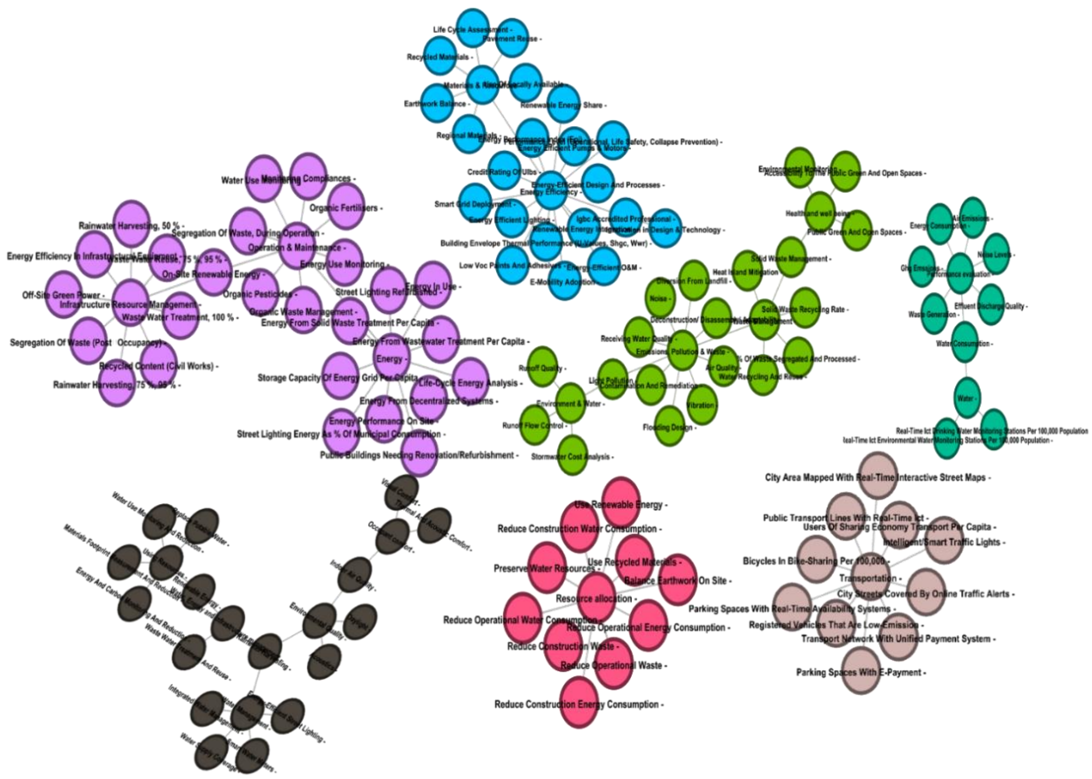

Figure 3: Community structure of the sustainability indicator network showing modularity-based clusters.

The analysis resulted in a high modularity value of 0.974, indicating a strong community structure within the network. A total of 113 distinct communities were identified, suggesting that the indicator network is highly fragmented into multiple, relatively independent groups. This high modularity value indicates strong clustering and limited interaction between groups, confirming a fragmented indicator structure. This highlights the nature of the existing sustainability assessment framework, given the large number of detected communities. Rather than forming an integrated, cohesive assessment system, the indicators tend to cluster by specific thematic domains, sectoral focuses, or framework origins. This implies that current frameworks do not adequately address interdependence among environmental, social, and economic dimensions.

Figure 3 illustrates the community structure of the indicator network, where distinct clusters are visible as separate groupings of indicators. Different groups of indicators were identified by modularity-based community detection, with each color representing a distinct cluster. Indicators in the same color category are more closely related than indicators in other groups.

Identification of Cross-Cutting Indicators

To address the fragmented community structure identified in the indicator network, cross-cutting indicators were identified using betweenness centrality as the primary metric. Based on this analysis, the first 15 indicators were selected to illustrate cross-cutting aspects from the total set of 387 quantitative indicators. These indicators exhibit the highest betweenness centrality values and span multiple modularity classes, confirming their role in bridging distinct indicator communities. Closeness centrality was examined as a supporting measure to contextualise their overall connectivity within the network.

Table 2 presents the identified cross-cutting indicators and their associated network metrics. These indicators provide an empirical basis for integrating fragmented sustainability frameworks and for developing a structured, hierarchical conceptual framework for public infrastructure. These indicators served as key inputs to the development of the conceptual framework presented in the subsequent section.

Table 2: Cross-cutting sustainability indicators identified using network analysis.

ID	Modularity Class	Closeness centrality	Betweenness centrality
Operation & Maintenance	64	0.5090909	278
Energy	64	0.4516129	225
Energy Efficiency	18	0.7586207	209
Emissions, Pollution & Waste	13	0.5	198
Infrastructure Resource Management	64	0.3733333	188
On-Site Renewable Energy	64	0.4375	171
Waste Management	13	0.46	152
Rainwater Harvesting	12	0.3921569	131
Materials & Resources	18	0.5789474	111
Water, Energy, and Infrastructure Management	12	0.3571429	97
Environmental Quality	12	0.3448276	93
Light Pollution	13	0.3833333	76
Solid Waste Management	13	0.359375	76
Renewable Energy	12	0.3076923	75
Using Resources	12	0.2631579	70

Conceptual Framework for Sustainability and Climate-Resilient Infrastructure Assessment

Based on the results of the network analysis, a conceptual framework was developed to support the assessment of sustainability and resilience in public infrastructure in the Indian context.

From the Modularity-based analysis, distinct thematic clusters were identified, and indicators were grouped based on their thematic similarity. These were further examined to identify key indicators using centrality measures. Based on their structural importance, relevance to the Indian context, and to avoid redundancy. A refined subset of 56 indicators was identified from the clustered network based on centrality analysis, thematic relevance, and contextual suitability. The framework is structured into three levels: indicators, criteria, and requirements, to enable systematic aggregation, comparison, and decision support. The framework is designed to support users in selecting indicators based on project-specific priorities by focusing on the refined subset of 56 indicators, which represent the most structurally influential and cross-cutting indicators identified through centrality analysis. Users can further tailor this subset by selecting relevant thematic clusters aligned with project goals and contextual requirements. *Figure 4* represents the conceptual framework.

By combining fragmented indicator groupings and prioritising system-level, cross-cutting indicators, the framework creates a consistent structure that can be applied to various public infrastructure sectors and decision-making contexts. At the highest level, criteria are consolidated into five broad requirements: (R1) Management and Governance, (R2) Social Well-being and Inclusivity, (R3) Environment and Resource Efficiency, (R4) Energy and Infrastructure, and (R5) Climate Resilience. These requirements serve as modular assessment dimensions that represent strategic sustainability and resilience goals.

At the lowest level, indicators represent measurable variables that capture the institutional, social, environmental, infrastructural, and resilience-related attributes of infrastructure systems.

These indicators are organised into criteria (C), which serve as intermediary aggregation units that represent distinct functional categories. Criterion-level aggregation allows normalisation and consolidation of heterogeneous indicators while preserving thematic coherence. The matrix-based layout of the framework facilitates cross-dimensional evaluation, allowing indicators under a single requirement to contribute to multiple criteria and enabling interlinkages between sustainability and resilience dimensions. Overall, the framework provides a transparent medium for evaluating, summarising, and benchmarking infrastructure projects. Unlike conventional frameworks that present static and often independent indicator lists, the proposed approach explicitly captures interdependencies among indicators, enabling the identification of cross-cutting indicators that enhance integration, reduce redundancy, and improve the coherence of sustainability assessment. It is intended to support evidence-based decision-making, policy formulation, and the prioritisation of interventions to enhance sustainability and climate resilience in public infrastructure systems. The framework enables users to systematically select and prioritise indicators based on their structural importance, thematic relevance, and alignment with project-specific requirements.

Implications for Practice and Research

Existing sustainability assessment frameworks are often fragmented, making decision-making complex and inconsistent across projects. This study provides a structured approach to identify and prioritise indicators using network-based metrics such as centrality, enabling practitioners, including project managers, planners, and policymakers, to focus on the most influential and cross-cutting indicators. The proposed three-level hierarchical framework facilitates systematic selection, aggregation, and comparison of indicators aligned with project-specific requirements, thereby supporting more transparent, consistent, and evidence-based decision-making in public infrastructure planning and evaluation.

From a research perspective, this study demonstrates the applicability of Social Network Analysis as a replicable, data-driven approach for examining interdependencies among sustainability indicators. The framework establishes a foundation for future work on indicator weighting, validation, and integration with multi-criteria decision-making methods, while also opening avenues for extending the approach to different infrastructure contexts and geographic settings. Overall, the study bridges the gap between indicator identification and practical application by offering a structured, scalable approach to sustainability assessment in infrastructure projects.

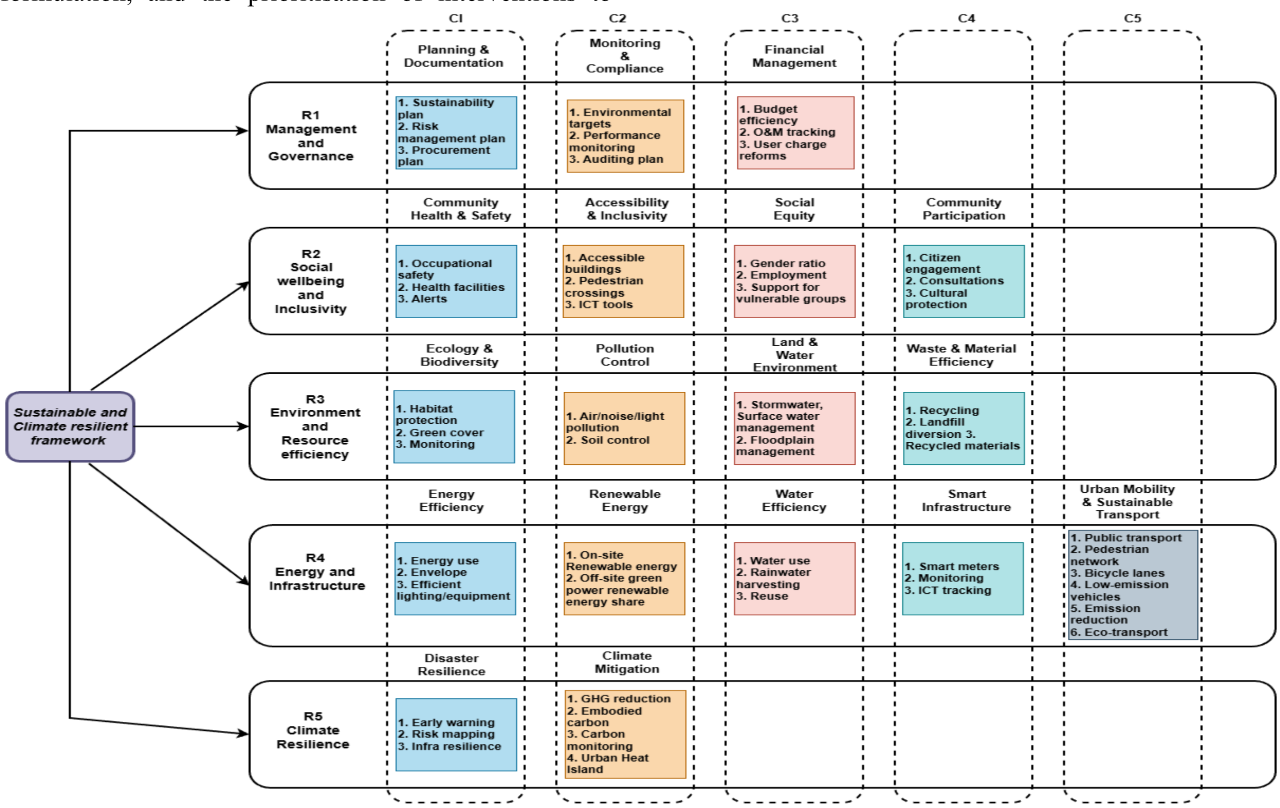

Figure 4: Conceptual sustainability and climate-resilience assessment framework illustrating the hierarchical organisation of indicator-level inputs into criteria and requirement-based modules for integrated evaluation of public infrastructure systems

Limitations and Future Research

On the one hand, this work proposes a conceptual framework for classifying sustainability indicators for public infrastructure. However, the framework is not validated through stakeholder engagement or real-world case applications, and no indicator weighting is performed in this study.

Additional research is required to validate and improve the suggested framework through expert consultation and stakeholder participation. Multi-criteria decision-making methods, such as the Analytic Hierarchy Process, can be employed to assign indicator weights and operationalise the framework. Furthermore, the framework could be extended to a representative set of case studies on public infrastructure projects in India to assess its practical usability and robustness. Periodic amendments to the indicator network should also be made to account for changes in sustainability priorities and climate resilience considerations.

Conclusions

This research develops a conceptual decision framework for sustainable and resilient public infrastructure in India by examining the structure and integration of existing sustainability indicators. A systematic review of global and Indian frameworks, codes, standards, and policy documents identified 629 indicators, which were classified as quantitative and qualitative. The relationships among the quantitative indicators were analysed using Social Network Analysis. The results reveal a highly sparse and fragmented indicator network with very high modularity of 0.974, indicating strong internal categorisation but weak cross-dimensional integration. This structural fragmentation points to limitations in prevailing sustainability frameworks, particularly in their support for integrated assessment of public infrastructure.

To address this limitation, the study identifies a focused set of cross-cutting indicators using centrality-based measures. These indicators capture key interconnections across multiple sustainability dimensions and provide a basis for improving coherence and integration. Based on the modularity analysis, indicators were grouped into different thematic clusters, and a refined subset of 56 indicators was identified from these clusters using centrality measures. Building on this insight, a conceptual decision framework is proposed that reorganises disjointed indicator sets into a context-sensitive structure suited to Indian public infrastructure. The framework supports transparent multi-criteria decision-making and provides a methodological and practical foundation for developing integrated, consistent, and climate-resilient infrastructure assessment and rating systems.

This is an ongoing study, and future work will focus on empirical testing, stakeholder engagement, and operational refinement of the proposed framework. The performance of the proposed framework can be benchmarked against existing frameworks through comparative case studies, evaluating criteria such as reduction in indicator redundancy, consistency in decision outcomes, and the ability to capture cross-dimensional linkages in sustainability assessment. The proposed framework benefits policymakers, infrastructure agencies, planners, asset owners, and researchers by providing a transparent, integrated basis for sustainability- and resilience-informed decision-making and assessment of public infrastructure.

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