A Systematic Review of Integrated Frameworks for Resilience and Sustainability Assessments for Critical Infrastructures

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ABSTRACT

There is a growing tendency to assess resilience and sustainability of critical infrastructures (CI), given the significant increment in high-impact natural hazard events affecting socio-economic welfare. Historically, these assessments have been conducted separately due to the independent evolution of each concept. However, recent contributions tend to integrate them. This paper provides a state-of-the-art review of integrated assessments for resilience and sustainability in CI, examining concepts, indicators, frameworks, and methodologies. Additionally, a Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis was performed to gain further insights into the prospects of integrated assessments. Following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology, eligibility criteria were established, leading to the selection of twelve studies. These works were compared based on five dimensions (economic, environmental, social, technical, and governance) to highlight the differences in the indicators used. While all studies considered the social, environmental, and economic dimensions, some did not further analyze sufficient indicators to evaluate environmental and social effects, with governance often neglected. This study emphasizes the relevance of establishing common metrics for a convergent frame for the resilience and sustainability assessment. The findings presented suggest that integrated assessments lead to a more strategic use of resources toward more resilient CI.

KEYWORDS

Critical infrastructures, Resilience Assessment, Sustainability Assessment, Integrated approach, Systematic Review, PRISMA Methodology, Extreme Events.

1 INTRODUCTION

Due to rapid urbanization, most of the world's population resides in cities. The United Nations (UN) reports a shift from 30% living in urban areas in the 1950s to 55% in 2018 (1–3). By 2050, it is projected that 70% of the global population will be urban, necessitating significant infrastructure investments of approximately one trillion dollars (3). This migration to urban areas burdens existing infrastructure responsible for vital services, making inhabitants more vulnerable to climate variability and associated costs (2,4,5). Economic losses from disasters have risen by 150% in the past two decades (3). For example, direct economic losses from disasters have increased by 150% in the last 20 years (6). Thus, increased investments are crucial to sustaining these services, contributing to economic growth and social well-being (2,7).

The global population has grown by over 6 billion in the last century, prompting a migration from rural to urban regions. This transition leads to a disproportionate consumption of primary resources used in human activities (1,8–10). Urban activities, including transportation, solid waste, and construction, contribute around 80% of greenhouse gas emissions, with the construction sector alone accounting for 30-40% (1,11–13). These activities have contributed to climate change for the last decades, which has amplified the frequency and intensity of natural extreme events such as floods, forest fires, hurricanes, and tsunamis, that impact severely the economy and society (8,14–16). Human-induced environmental impact has exacerbated these events, leading to notable disasters like widespread forest fires in Portugal, Spain, Brazil, and California (3,11,17).

1.1 Background and key terms

Infrastructure encompasses physical structures and facilities comprising the built environment, including roads, bridges, buildings, power networks, dams, and more (18). Infrastructures that are crucial for governance, commerce, and economic growth, are often referred to as critical infrastructures (18). Critical infrastructure is defined differently across countries and cultural contexts (19–22). The European Council defines it as "an asset, system, … essential for the maintenance of vital societal functions … and the disruption or destruction of which would have a significant impact in a Member State as a result of the failure to maintain those functions" (19,21,23).

Securing and protecting critical infrastructures is vital, requiring an understanding of potential hazards, risk analysis methods, and risk management models to improve the security of Critical Infrastructures (CIs) against extreme events (EE) (4,24,25). This involves the probability of occurrence of an EE with the identification of vulnerabilities and the predicted impact and consequences on the CI (4,16,25,26). Risk to infrastructure arises from the interaction of hazardous events with human and infrastructure exposure, capabilities, and vulnerabilities (17,27).

A hazard is a damaging and impactful phenomenon, while exposure assesses risks to people and infrastructure, and vulnerability reflects the predisposition to hazards (17,27,28). The European Commission defines risk management capabilities as the ability to reduce, mitigate or adapt to risks to an acceptable level (29). Risk assessments face uncertainties in forecasting impacts and managing events, making it difficult for CI to withstand threats without major impacts (30,31). Resilience assessments, along with risk management models, enable effective solutions to accelerate CI recovery and mitigate threats through quantifying decision-making (15,16,32–34). Resilience is defined diversely across disciplines and has a rich history (17). For example, the United Nations Office for Disaster Risk Reduction (UNDRR) defines resilience as "the ability of a system … to withstand, absorb, adapt, transform, and recover from the effects of a hazard … by maintaining and restoring its essential basic structures and functions through risk management" (9).

The Brundtland Report in 1987 initiated sustainable development, unfortunately, efforts to reduce human-related activities' impacts have been insufficient (1,5,6,11,32,35–38). The World Commission defines sustainability as "the ability to meet the needs of the present without compromising the ability of future generations" (6,39,40). Sustainable development encompasses economic, social, and environmental impacts, promoting compact, affordable, and innovative designs, livable communities, and essential social services (11,25,33,39,41). EE hamper sustainable development, causing significant societal and economic consequences, and infrastructure damage (31,33,39,42,43). Thus, applying sustainable practices to CIs becomes essential (44).

In 1992, the United Nations Conference on Environment and Development (UNCED) established principles for sustainable development, leading to Agenda 21, promoting actions for developed and developing nations (4–6). The Rio+10 World Summit in 2002 reinforced environmental preservation under Agenda 21 (4–7). The UNCED (Rio+20) led to the development of the 17 Sustainable Development Goals (SDGs) (4–6). The 2030 Agenda for Sustainable Development, adopted in 2015 these SDG, addresses poverty, inequality, economic growth, climate change, and environmental protection (7,10). Several SDGs focus on transforming CIs into sustainable and resilient infrastructures.

1.2 Resilience in relation to infrastructures

Critical infrastructure resilience aims to reduce the impact caused by EE, absorb disruption, and recover quickly (17,27). Bruneau et al. (45) resilience definition emphasize the system's ability to reduce, absorb, and recover from shocks, highlighting four properties namely, robustness, redundancy, resourcefulness, and rapidity (9,32,33,45).

Risk management methods struggle with addressing low-probability high-impact hazards (4). Resilience assessments, on the other hand, recognize the need for CI preparedness against uncertain and unexpected threats. The concept of resilience has gained importance among policymakers and researchers as it ensures reduced functional limitations and timely recovery of CIs (15,30,32,42). Integrating risk and resilience in a comprehensive approach avoids oversimplification and supports effective response, preparedness, and recovery of CIs during and after EE (17,27). New methods need to address the complexities of EE and the need for managing uncertainties (13,15,32,46,47). Therefore, for this study, proactive resilience assessment includes risk assessment for managing CI effectively.

Resilience is a key focus in international politics, aligned with the 17 SDGs. The Sendai Framework for Disaster Risk Reduction (SFDRR) adopted in 2015 aims to reduce risks and enhance resilience globally (8,12). It shares common goals with the SDGs, emphasizing resilience at all levels through economic, social, and technological measures (7,8,12,13). The framework sets targets for 2030 emphasizing resilience at all levels by including economic, legal, structural, social, educational, environmental, political, institutional, and technological levels (8,12,13). It has generated documents on nature-based solutions for disaster risk reduction and youth involvement in disaster risk reduction and building resilience (12). To support its implementation, the UNDRR published the Principles of Resilient Infrastructure in 2022, guiding nations in ensuring the viability of critical services provided by CIs. These principles enhance understanding, support planning, and aid in developing risk-based policies for CI projects (9).

Some standards and guidelines have emerged worldwide emphasizing the importance of protecting CIs, and providing some minimum requirements for managing and optimizing CI’s resilience (14). The NFPA1600 is a non-governmental standard by the National Fire Protection Association, adopted by the U.S. Department of Homeland Security, providing guidelines for disaster and emergency management to ensure CI functionality during disruptive events (48). Other standards like ISO 22320:2018 (emergency management) (49), ISO 22301:2019 (business continuity management systems) (50), and AS/NZS 5050 (Business Continuity for Managing Disruptions in Australia and New Zealand) (51) focus on emergency and business continuity management.

As for risk management ISO 31000:2018 (52) is a widely used risk management standard that provides principles, guidelines, and strategies to assess and analyze risks, reduce hazards, and improve stakeholder understanding and management processes, resulting in improved risk management practices. Despite relevant criticism from researchers (15), this standard is crucial for organizations as it provides understandable terminology, and management processes, and improves the average level of risk management (15,16).

Few standards exist for CI resilience. Examples exist focused on organizational resilience from the International Organization for Standardization (ISO) as ISO 22316:2017 (Security and resilience - Organizational resilience) (53) and BSI 65000:2014 (Guidance for Organizational Resilience) (54), promoting consistent approaches to threat identification, policy integration, and flexibility to address unexpected threats in the European context (17). ASIS SPC.1-2009 (Organizational resilience standard) (24) from the United States provides guidelines for security, resilience, risk assessment, and emergency response. The ISO /WD 22372 (55) is being developed for resilient infrastructure to ensure critical service delivery, involving various stakeholders. These efforts highlight the progress and need for disaster preparedness standards.

1.3 Sustainability in relation to infrastructures

Sustainable infrastructure evolved from green buildings to green infrastructure, considering the so-called triple bottom line with economic, social, and environmental impacts for sustainability (1,35,37,44). Sustainable CI aims to improve society's quality of life by reducing impacts through optimized life cycle design and management (31,36). The SDGs created in 2015 align with transforming CIs into sustainable infrastructures: ensuring water resources, renewable energy, resilient infrastructure, sustainable cities, production and consumption, climate action, and biodiversity protection (7,8,10,11). The Paris Agreement emphasizes limiting global warming and requires nations to reduce Greenhouse gases emissions and resilient-building towards climate change impacts (7,8,11).

Unlike resilience, sustainability lacks comprehensive standards and guidelines for CI sustainability. Standards like ISO 37120:2018 (Sustainable cities and communities) (56) and ISO 37101:2016 (Sustainable development in communities) (57) focus on cities and communities, measuring urban services, quality of life, and promoting holistic community development with sustainability goals. Lastly, the PAS 2080 (58) specification (carbon management infrastructure), guides organizations in enhancing sustainability and reducing carbon emissions across the lifecycle of infrastructures like buildings and roads, emphasizing carbon reduction strategies throughout the project's lifecycle.

Various methodologies and tools have emerged to evaluate sustainability, encompassing different scopes, criteria, and indicators (35,36). However, sustainability assessments serve as decision-making processes, considering diverse perspectives to enhance sustainable solutions (37). Their significance lies in establishing a systematic framework that integrates expert opinions and technical knowledge for precise and rigorous decision-making in CI contexts (35,36,39).

Initially, these methodologies focused on appraising environmental impacts, with Life Cycle Assessment (LCA) being a prominent tool (37). LCA examines environmental effects throughout an infrastructure's life cycle or specific phases, involving four steps: objective definition, current analysis, impact assessment, and result analysis (35,37). Furthermore, life cycle cost analysis (LCCA) facilitates economic evaluations of different life phases (35).

Some sustainability rating systems initially designed for building sustainability, such as Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Methodology (BREEAM), Level(s), and GBTool, have extended their application for evaluating infrastructure sustainability, tailored to specific national requirements (6,59). While these methods originated from assessing building performance, they have evolved to gauge the sustainability of CIs, utilizing diverse qualitative indicators (10,25,59,60). Widely employed, these assessment systems offer rankings for "green infrastructures" (10,25,59,60), promoting sustainability in CI projects by creating awareness and aiding project design and post-occupancy evaluation, although compliance is not mandatory (61).

LEED, BREEAM, and Level(s) are three prominent sustainability rating systems examined here. LEED assesses a building's environmental performance holistically throughout its life cycle. It adopts a points-based approach in five categories, totaling 100 points, resulting in certifications: basic, silver, gold, and platinum (6,61). BREEAM evaluates a building's performance across various categories, including water, energy, materials, health, and transportation (6,61). Each category holds defined requirements and weighted significance, contributing to an environmental performance index ranging from zero to 100. The index determines the building's certification level, ranging from "Excellent" to "No classification" (6,61). Level(s) employs key sustainability indicators to assess the carbon, materials, water, health, comfort, and climate change impacts across the entire life cycle of a building. This adaptable approach serves as a valuable tool for identifying critical sustainability areas and ensuring the long-term viability of buildings and cities (62,63).

1.4 Research questions

Limited research has explored the integration of sustainability and resilience assessments for CI (61,64). Governments worldwide have recognized the significance of resilience and sustainability, resulting in the development of policies and procedures (3). The importance and necessity of sustainability and resilience for CIs are evident from various policies, agendas, rating systems, and standards (see sections 1.1 and 1.3). While sustainability and resilience were initially approached separately, the current context emphasizes the need for an integrated approach, as exemplified by the 17 SDGs. Integration of resilience and sustainability is crucial for the effective functioning of CIs, which provide essential services to society.

Hence, the authors recognize the significance of a systematic literature review that explores the merging of sustainability and resilience. Following the suggestions of Blaikie (65), this review aims to examine the current state of knowledge regarding the established research questions. It is important to emphasize that this paper does not aim to review general concepts of sustainability and resilience, key technologies, or industrial applications, instead, it focuses on integrated frameworks and methodologies that have assessed the sustainability and resilience of CI to natural hazards, and their contribution to improving these attributes for these infrastructures. The research questions are:

- What evidence exists in the literature on the importance of integrating resilience and sustainability assessments for CIs?
- What are the opportunities and challenges of an integrated resilience and sustainability assessment method for CI?
- What characteristics share the studies that proposed an integrated approach for CI?
- What are the gaps and limitations in the existing research?
- How can future research close the existing research gaps?

2 RESEARCH METHODOLOGY

This study employed a systematic literature review following the PRISMA guidelines to examine methods and frameworks for integrated assessment of resilience and sustainability in critical infrastructures. While PRISMA is primarily designed for medical research, it has been adapted by engineering authors, offering comprehensive guidance for systematic review presentation. The review process consisted of four main steps: establishing eligibility criteria, identifying information sources, conducting the study selection, and collecting data (3,10,11,34,66,67).

2.1 Eligibility criteria

To ensure the quality of the review, strict filters were applied to select relevant articles within the fields of resilience and sustainability. Table 1 provides a clear overview of the eligibility criteria used. The exclusion criteria were carefully designed to maintain focus on the study objectives and ensure the inclusion of high-quality publications. Each exclusion criterion was evaluated twice to enhance accuracy and minimize errors.

Table 1. Eligibility criteria

Inclusion Criteria	Exclusion Criteria
• Peer-reviewed publications.	• Pre-2015 and non-English studies.
• Publications focusing on critical infrastructure identification and protection.	• Publications not focused on critical infrastructures (CI).
• Resilience assessment studies for infrastructures.	• Studies assessing human-made hazards.
• Studies evaluating the sustainability of infrastructures.	• CI resilience is not comprehensively assessed, limited focus on critical elements rather than a holistic assessment of CI.
• Studies assessing resilience and sustainability of infrastructures.	• Studies lacking assessment of economic, environmental, and social dimensions in CI sustainability.

This research primarily examined academic journal articles published after 2015, considering the adoption year of the Sendai Framework for Disaster Risk Reduction, the Paris Agreement, and the 2030 Agenda with the 17 Sustainable Development Goals (as discussed in sections 1.1, 1.2, and 1.3). Due to human-induced activities, climate change had an impact on natural EE like floods, forest fires, hurricanes, and tsunamis that have become more frequent and intense, causing significant impacts on the economy and society (8,14–16). Therefore, this review specifically focuses on natural hazards to address the consequences of these human activities. Excluding studies on human-made hazards also allows for a manageable analysis within the resource and scope limitations of this study. Concentrating on natural hazards permitted us to conduct a more focused and comprehensive review of the available literature on this specific topic.

2.2 Information sources and search

The electronic databases Scopus, Science Direct, Taylor & Francis, ASCE library, and SpringerLink were searched, along with tools like Google Scholar, from March 8, 2022, to July 13, 2022. The search terms included were "Risk assessment," "Risk management," "Resilience assessment," "Sustainability assessment," "Sustainable," "Resilient," "Infrastructure," "Critical Infrastructure," "Civil Infrastructure," "Critical Infrastructure," “Frameworks,” and “Methodologies”. Synonymous terms were used to broaden the range of studies and minimize bias. Boolean operators "OR" and "AND" were employed to cluster and structure the search equation.

2.3 Study selection

The eligibility assessment was conducted by one author (OU) based on the criteria. Study selection results were reviewed by two authors (AF, ET) to ensure compliance with systematic review requirements. A total of 259 studies (including 8 doctoral dissertations) were initially identified. After removing duplicates and applying eligibility criteria, 145 studies were excluded based on title, abstract, and keywords. A full-text screening was performed on the remaining 93 papers, leading to the exclusion of 73 studies. The remaining publications underwent a full-text review based on eligibility criteria, resulting in eight studies for theoretical analysis in section 3.4. Ultimately, twelve papers were selected for the systematic review. The flow diagram in Figure 1 illustrates the step-by-step literature search process.

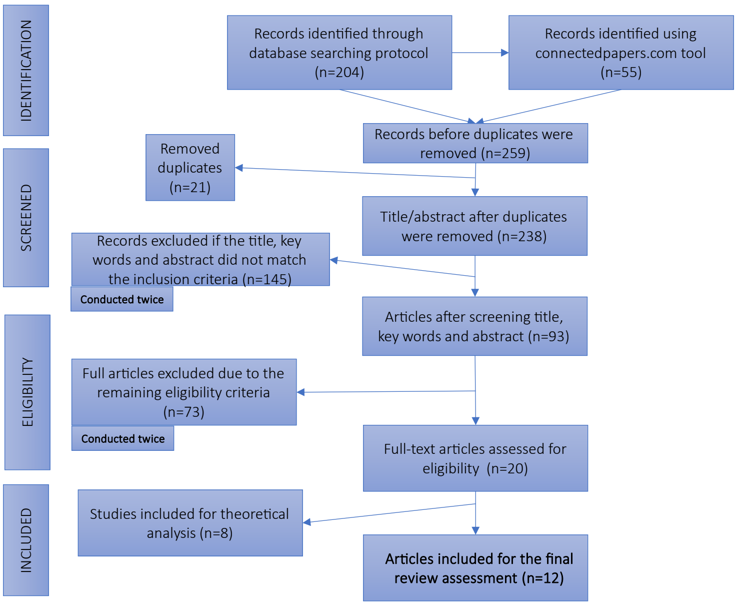

Figure 1. Application of the PRISMA guidance flow diagram for Literature Search Strategy (based on (68)).

2.4 Data collection process and summary measures

Data extraction involved creating a sheet to collect key information from selected studies. The collected data included publication year, the problem addressed, infrastructure type, hazard type, the solution proposed, indicators considered, methodologies and frameworks used, dimensions assessed, and findings. Review and extraction were performed by one reviewer (OU) and verified by two reviewers (ET, HS), with disagreements resolved by a fourth reviewer (AF).

3 PRESENTATION AND DISCUSSION OF RESULTS

3.1 Study selection

A bibliometric network graph was created using VOSviewer software. The graph was based on text data extracted from titles and abstracts of selected papers (used in sections 3.2 and 3.4). The text was obtained from selected papers exported in ris format from the Mendeley reference manager. Figure 2 shows a co-occurrence map of terms that appeared at least five times in the titles and abstracts. Relevance was determined by the software, with terms like "theme" and "paper" deemed less insightful. Terms such as "resilience," "sustainability," and "infrastructure" were retained, along with their linked terms. The strong correlation between resilience, sustainability, and other terms in Figure 2 indicates their importance in integrated research on this topic.

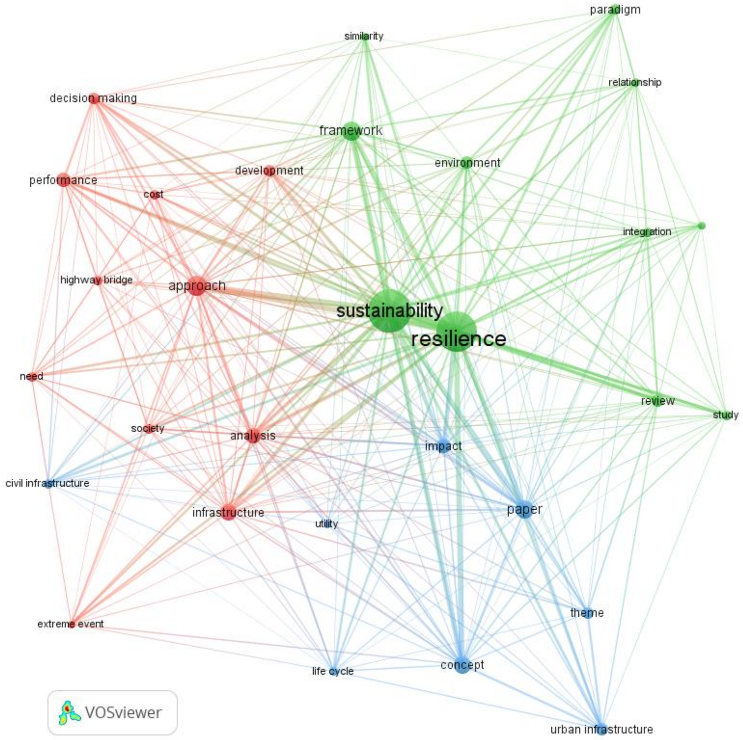

Figure 2. Network of selected terms and their correlation in the literature of CI’s resilience and sustainability assessment.

3.2 Characteristics, conceptual frameworks, and methodologies

To address the first research question (What evidence exists in the literature on the importance of integrating resilience and sustainability assessments for CIs?) this study systematically examines and categorizes relevant research that has undertaken this integration. In this section, it is provided a comprehensive overview of how these studies approached the evaluation of both resilience and sustainability, highlighting their shared characteristics and the parameters they analyzed. A total of twelve studies that meet the eligibility criteria specified in section 2.1 were included. These studies introduce novel concepts, which are grouped into two categories, as illustrated in Figure 3.

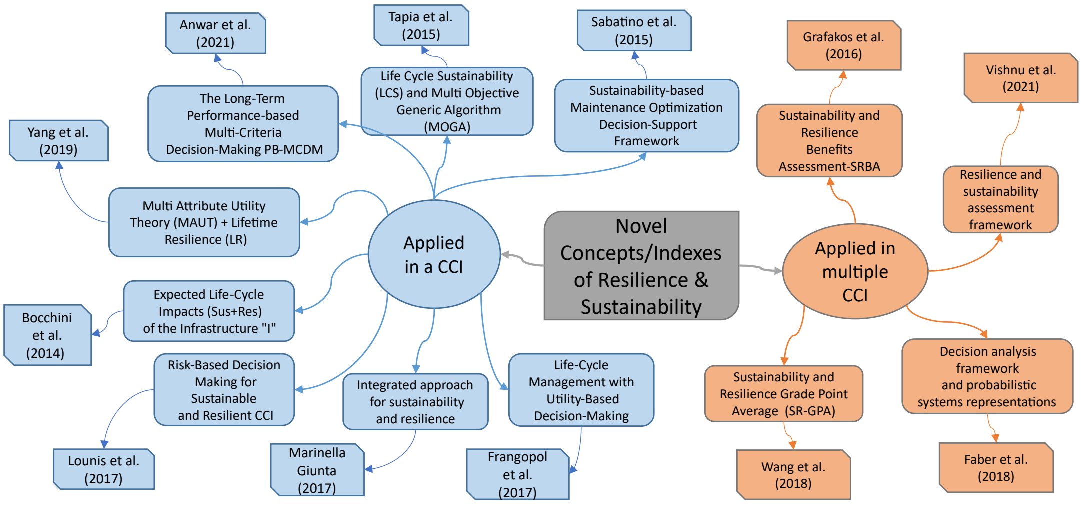

Figure 3. New concepts proposed to integrate resilience and sustainability assessment.

These new concepts aim to obtain the best option/alternative for a post-event retrofitting-rehabilitation scenario or to assess the state in each phase of the life cycle of the infrastructure assessed for sustainability and resilience. Three clusters were created to group studies with similar methodologies to facilitate their analysis and comparison of similar and different characteristics (these studies and their main features are presented in Table 2):

Table 2 Integrated approaches of sustainability risk and resilience, and its main features.

ID	**Group**	**I. Type**	**Hazard**
Wang Liang et al. (69)	A	Road	Seismic
Grafakos et al. (70)	A	Urban CI	Climate change effects
Sabatino et al. (71)	B	Bridge	Environmental agent
Frangopol et al. (47)	B	Bridge	Environmental agent
Yang et al. (72)	B	Bridge	Decay, Environmental agent
Tapia et al. (73)	B	Road	Seismic
Giunta, Marinella (74)	C	Road	Seismic, landslide, floods
Lounis et al. (75)	C	Bridge	Seismic, Environmental agent
Bocchini et al. (76)	C	Bridge	Seismic
Vishnu et al. (77)	D	Road	Seismic
Anwar et al. (78)	D	Urban Buildings	Seismic
Faber et al. (79)	D	Urban CI	Geo-hazard

Studies allocated in group A within Table 2, follow a hierarchized structure that adopts a bottom-to-top framework, as each of them defines a series of indicators that form categories that subsequently, conform to dimensions whose assessment would give the final performance score/index.

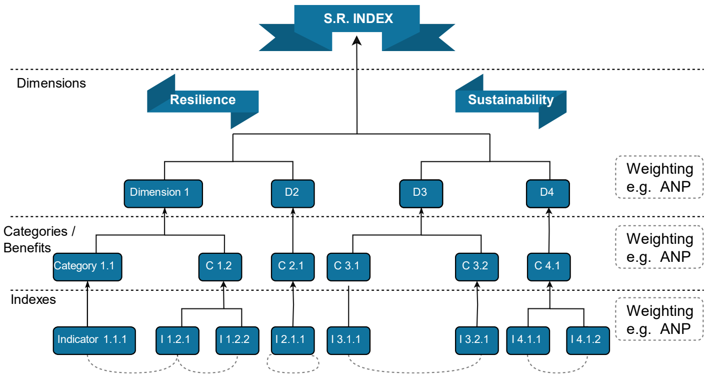

Figure 4. General sustainable and resilience assessment framework corresponding to group A.

Grafakos et al. (70) introduced the Sustainability and Resilience Benefit Assessment (SRBA), which incorporates resilience within social, environmental, and economic indicators. The methodology consists of seven steps: project identification and characterization, the establishment of expected benefits and indicators, development of the baseline scenario, creation of the project scenario (including direct and indirect effects), quantification of scenario differences, and creation of a matrix of sustainability and resilience benefits. One notable aspect of this contribution is the integration of Geographic Information System (GIS) tools, enabling stakeholders to quickly consider scenario aspects. The study presents benefits in a matrix that compares the performance of the CI in the baseline scenario and proposed solutions in the project scenario. The results demonstrate opportunities to enhance resilience and sustainability based on the comparisons made.

Wang et al. (69) proposed the methodology of Sustainable Resilience-Grade Point Average (SR-GPA), which is essentially a ranking method for assessing sustainability by introducing a parallel assessment that includes resilience in one or more dimensions, as shown in Figure 4. The SR-GPA index is made up of five dimensions, divided into essential quality (demand, status, influence, and resource dimensions) representing CI sustainability, and expanding quality, which includes the measure dimension for resilience. The assessment indexes consist of qualitative and quantitative indexes. Qualitative indexes describe aspects that are not easily quantifiable, while quantitative indexes can be directly measured using quantitative data. Quantitative indexes are further divided into benefit indexes and cost indexes based on their impact on urban infrastructure GPA. Benefit indexes have a positive impact, while cost indexes have a negative impact.

Studies in group B (Table 2) performed multi-objective optimization techniques to assess CI's resilience and sustainability. Attribute values were obtained and transformed into standard measurements through normalization methods like multi-attribute utility theory (MAUT). The results were analyzed to identify the optimal solution for the CI, and the best alternative was selected. The general framework of the studies can be observed in Figure 5.

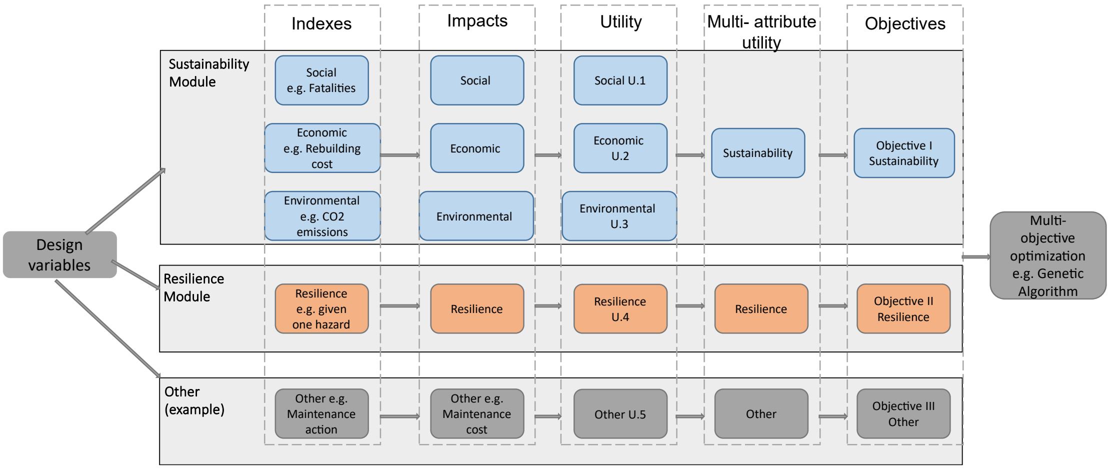

Figure 5. General multi-objective optimization framework corresponding to group B based on (47,71,72).

Frangopol et al. (47) followed a similar procedure as the one depicted in Figure 5, quantifying sustainability impacts and transforming them into utility values. Notably, the authors included fatigue and fracture analysis and employed structural health monitoring for time-variant performance. This enables obtaining optimal management solutions aligned with objectives and constraints. Unlike (71,72), Frangopol et al. (47) did not use genetic algorithms (GA) for optimization but aimed to maximize utility values to enhance sustainability and resilience in CIs.

Sabatino et al. (71) conducted a risk assessment for a bridge, considering increasing live loads and environmental agents like chloride contamination. Time effects were simulated by applying higher live loads and reducing beam and slab reinforcement cross-sections. Maintenance actions were quantified if the resilience performance indicator (RPI) exceeded a predefined threshold. MAUT was used on a sustainability module and was also applied to maintenance investment costs. To determine optimal intervention strategies, GA was employed, following a flowchart until the criteria were met and the optimal alternative was identified.

Yang et al. (72) also followed the framework principles depicted in Figure 5. They incorporated a deterioration model to evaluate structural performance considering corrosion, fatigue, and other adverse effects. Additionally, (72) quantified a reliability index for structural performance over time. Moreover, they introduced a generic quantification model based on linear approximation and reliability indexes to assess resilience during different stages, named Lifetime Resilience (LR). LR evaluated by aggregating hazard impacts using deterioration and resilience models, represents the life-cycle resilience performance index of the CI. The approach pursues three optimization objectives: enhancing sustainability, deterioration intervention, and resilience (multiple hazards) utilities. Like (71), Yang et al. (72) employed a GA method to determine optimal intervention strategies for each utility value obtained.

Tapia et al. (73) introduced a distinct approach in Group B by combining a genetic algorithm (GA) with a multi-objective (MO) process, resulting in the MOGA process, integrated into a life-cycle sustainability (LCS) analysis. The MOGA process identifies optimal alternatives to mitigate sustainable performance impacts caused by natural hazards on the CI. This method generates parameters representing repair actions for different CI components. The process begins with a population of chromosomes representing repair and improvement options for affected CI elements. Fitness functions, including a reliability index and six LCS indicators, are evaluated iteratively to achieve sustainability and resilience objectives. The LCS-MOGA process is evaluated over the entire service life of the CI.

In Group C, researchers proposed a life-cycle framework for quantifying structural performance and improving the design and maintenance of CIs during extreme events (EEs), while considering additional sustainability aspects. The focus was on mitigating the anticipated impacts of predefined rehabilitation/retrofitting alternatives and selecting the optimal solution. Two studies utilized the life-cycle cost (LCC) tool to identify the alternative with the lowest expected LCC, offering the best outcome.

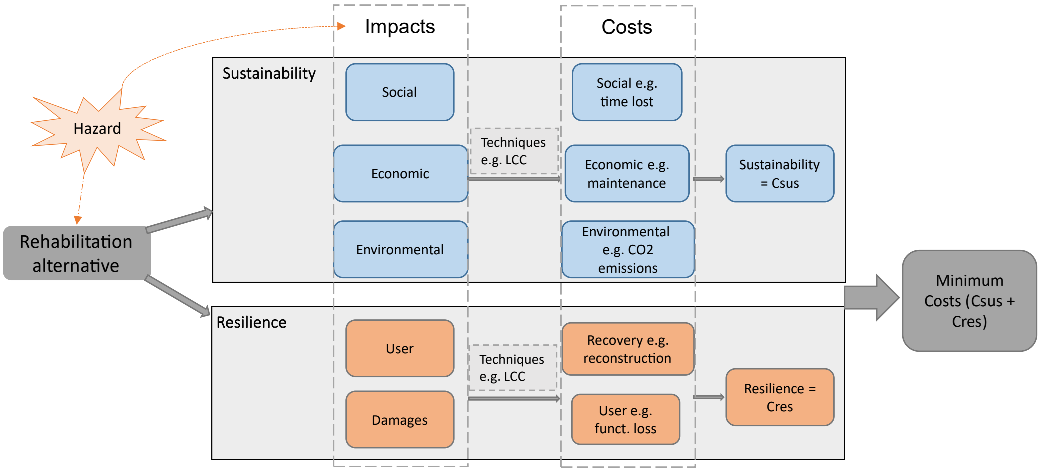

Figure 6. General life-cycle costs optimization framework corresponding to group C based on (74,76).

Marinella Giunta (74), followed a similar procedure as the one depicted in Figure 6, considering economic, and temporal aspects in the initial stages. The subsequent phase involves a robust LCCA, encompassing environmental factors such as carbon dioxide emissions, embodied energy, and solid waste generation. Within this framework, each rehabilitation option is evaluated based on two overarching costs: sustainability and resilience. Ultimately, the optimal rehabilitation solution is chosen based on the minimum sum of sustainability and resilience costs.

Bocchini et al. (76) proposed a method comparable to (74) for assessing the life-cycle impact of the CI on the community. The study employed LCA and external cost calculation to evaluate the CI's implications on the economy, ecology, and society. LCA considered impact categories such as global warming potential and total primary energy. LCC encompassed maintenance actions, user expenses, and economic impacts on non-road users, such as traffic jam costs during repairs. To determine the overall sustainability of the CI, (71) assigned weights to each calculation based on the decision-makers preferences. They quantified direct and indirect impact costs for resilience assessment. A seismic fragility analysis was conducted, and the results were combined with bridge construction costs to estimate direct costs. Indirect costs related to EE were evaluated, considering vehicle detours and the impact on the crossed highway. The sum of sustainability and resilience impact costs yielded the overall impact costs of the CI.

Lounis et al. (75) assessed sustainability and resilience by considering various hazards. Regarding sustainability, they examined the impact of corrosion degradation on the lifecycle and its effects on costs, the environment, and society. For resilience, they analyzed structural safety, recovery time, and functionality during seismic hazards. To achieve sustainability, the authors set performance goals, regarding environmental, social, and economic impacts. They developed a model to assess maintenance, repair, and rehabilitation costs based on the time-varying probability of bridge deck failure due to corrosion. For resilience, functionality and recovery time were established as performance goals for seismic events. Damage levels and functionality loss were quantified, considering the impact of corrosion degradation, and using seismic-dependent fragility curves.

The last group (D) of studies begins by assessing the performance of the CI and quantifying the social, environmental, and economic impacts. These studies follow a Multi-Criteria Decision-Making (MCDM) approach to analyze the obtained results of all the assessed criteria.

Faber et al. (79) proposed a framework for assessing the resilience and sustainability of an interlinked system. They emphasized the hierarchical governance structure and time-slicing modeling to evaluate system performance. The authors considered probabilistic analysis, assessing robustness and sustainability failure. Environmental impact was evaluated through CO_2 emissions, while the social aspect incorporated Life Quality Index (LQI) indicators. The economic dimension considered GDP and costs associated with the construction and reconstruction of the CI. A life-cycle model was used to analyze system capacity and benefit scenarios, ensuring a comprehensive assessment of resilience and sustainability.

Anwar et al. (78) introduced a Performance-Based Multi-Criteria Decision-Making (PB-MCDM) methodology consisting of four modules: performance assessment and resilience assessment for resilience evaluation, and long-term sustainability analysis for sustainability assessment. The study converts the resulting implications (e.g., seismic loss, sustainability, and resilience) into criteria attributes, and ranks rehabilitation alternatives using a decision-making method.

Lastly, Vishnu et al. (77) studied road network sustainability and resilience during transportation hazards. Sustainability was evaluated based on repair costs, repair emissions, carbon dioxide emissions, and missed trips, while resilience was assessed using travel time and distance. Probabilistic methods were used to analyze these metrics under different earthquake scenarios. Additionally, a correlation analysis using Gaussian mixture-based clustering approach was performed, revealing a weak correlation between resilience and sustainability metrics. This highlights the importance of conducting both analyses and employing integrating methods for effective hazard mitigation and recovery planning.

3.3 Key indicators

Addressing the third research question (What characteristics share the studies that proposed an integrated approach for CI?), an exhaustive analysis of indicators utilized across all twelve studies was conducted. The assessment of both resilience and sustainability necessitates the contemplation of various dimensions, encompassing environmental, social, economic, resilience, and organizational aspects. Consequently, indicators were meticulously compiled and linked to these dimensions. Table 3 provides a comprehensive compilation of indicators utilized in each study, along with details about the infrastructure type and the hazard investigated in each case for clarity.

Seven out of the twelve studies conducted a comprehensive analysis by including an indicator for risk assessment of the CI. The resilience assessment in the study (72) considers multiple hazards and quantifies resilience over time using the Lifetime Resilience concept. However, (71) proposes a bridge analysis that incorporates resilience, risk, and sustainability, encompassing the three pillars. Nevertheless, (71) should include additional attributes, particularly for social and environmental impacts. In studies (47), (72), and (71), resilience assessment is effectively integrated into sustainability assessment through the multi-attribute theory, enabling the consolidation of diverse values into a representative index. Notably, Frangopol et al. (47) enhance resilience assessment by incorporating fracture and fatigue analysis and structural health monitoring, resulting in a robust evaluation.

Table 3. Summary of indicators included in the integrated assessments for different CI and hazards by authors.

Dimension	**Indicator**	**Author (Reference)**											
		Faber et al. (79)	Grafakos et al. (70)	Frangopol et al. (47)	Yang et al. (72)	Sabatino et al. (71)	Lounis et al. (75)	Giunta Marinella (74)	Tapia et al. (73)	Bocchini et al. (76)	Vishnu et al. (77)	Anwar et al. (78)	Wang Liang et al. (69)
Environmental	CO_2 emissions	χ U	ϴ U	Δ B	Δ B	Δ B	Δ B	Ω R	• R	• B	• R	• H	• R
	Resource consumption/ conservation		ϴ U										• R
	Biodiversity		ϴ U										
	(Re)Construction Waste disposal		ϴ U		Δ B		Δ B	Ω R	• R				• R
	Climate change impact		ϴ U				Δ B						
	Energy consumption			Δ B	Δ B	Δ B							• R
	Local materials usage												• R
	Recycling												• R
	Embodied Energy								• R	• B		• H	
	LCA									• B			
Economic	Growth GDP	χ U	ϴ U										• R
	Maintenance cost	χ U		Δ B		Δ B		Ω R	• R	• B			
	Inf. Functionality		ϴ U										
	Life cycle costs						Δ B	Ω R		• B		• H	
	Increased user costs				Δ B		Δ B	Ω R		• B			
	Repair-rebuilding costs			Δ B	Δ B	Δ B	• B	Ω R	• R	• B	• R		
Social	Welfare	χ U	ϴ U										• R
	Health	χ U	ϴ U										• R
	Education		ϴ U										• R
	Time loss			Δ B	Δ B	Δ B	Δ B	Ω R	• R	• B	• R		
	Extra travel distance			Δ B	Δ B	Δ B	Δ B	Ω R		• B	• R		
	Casualties			Δ B	Δ B	Δ B			• R			• H	
	Infrastructure investment												• R
	Noise pollution												• R
	Cultural and local protection												• R
Organizational / Governance	Infrastructure functionality	χ U	ϴ U							• B			
	Coordination between institutions	χ U	ϴ U							• B			
	Creation of awareness		ϴ U										
	Public satisfaction												• R
	Supply capacity												• R
	Intelligent monitoring system												• R
Technical: -Resilience	Reliability index	χ U		Δ Ω B	Δ B				• R				
	Robustness	χ U						Ω R				• H	• R
	Functionality loss	χ U		Δ Ω B	Δ B		Δ • B	Ω R	• R	• B	• R	• H	
	Climate change impact		ϴ U										• R
	Recovery time						• B				• R	• H	
	Structural Performance			Δ B						• B		• H	
-Risk Assessment	Risk reduction		ϴ U	Δ Ω B	Δ B	Δ B	Δ • B						• R
	Damage levels			Δ Ω B			Δ • B		• R			• H	

Hazards are represented with the following symbols: Seismic •; Environmental agent Δ; Geo-Hazards χ; Climate change effect ϴ; Undefined Ω. Infrastructure types are represented with the following symbols: Bridge: B; Urban Buildings: H; Road: R, Undefined: U.

In contrast, Lounis et al. (75) conducted a separate assessment of the resilience and sustainability of the CI. Their approach included a risk assessment considering the safety and serviceability of a highway bridge. To evaluate bridge resilience under a specific peak ground acceleration, fragility curves were employed to estimate structural degradation. The comparison of different deck alternatives revealed that a high-performance concrete deck offered a more resilient (and sustainable) option for the case study.

Marinella Giunta (74) assessed resilience focusing primarily on CI rehabilitation without considering the pre-event situation. Additionally, the analysis in (74) accounted for direct costs associated with retrofitting options in the social and environmental domains. However, this monetary approach facilitates stakeholder decision-making, such as government or private companies, in identifying the most resilient and sustainable retrofitting options, as economic considerations tend to be prioritized.

Among the twelve studies, most demonstrate extensive data availability, and high data quality, and utilize complex models and simulations for the assessment. Vishnu et al. (77) exemplify this, conducting approximately 4000 network analyses for seismic scenarios across various periods in their highway network case study. The authors also employed Gaussian mixture-based clustering analysis to correlate sustainability and resilience metrics, using data from the network analyses (i.e., missed trips, travel distance, travel time, emissions, repair costs, and emissions). Interestingly, the analysis revealed a weak correlation between resilience and sustainability metrics for longer periods, emphasizing the necessity of conducting both assessments as they cannot be interchangeable.

Faber et al. (79) utilized simulation results as discrete variables and applied a saturated Bayesian Network to examine interdependencies between hazard, robustness, losses, recovery, materials, resilience, and LQI. Correlations were found between LQI, resilience margin, recovery time, material consumption, and the robustness index, indicating dependence on failed system components. A Cobweb plot was created to visualize the relationship between 1000 scenarios and model variables, revealing that higher preparedness limited losses to a maximum of 60%.

Among the twelve studies, only Grafakos et al. (70) provide semiquantitative outputs as they present benefits in a matrix mapped with GIS, analyzing resilience in social, economic, and environmental indicators without quantification.

All studies in Table 3 assessed, to a greater or lesser degree, the three pillars of sustainability (economic, environmental, and social) and the technical domain, contributing to their analysis with resilience assessment. Only four studies evaluated all five dimensions, including the organizational domain (Bocchini et al. (76), Faber et al. (79), Wang et al. (69), and Grafakos et al. (70)). Bocchini et al. (76) focused on management, maintenance, and contingency response in the CI, adapting indicators for different stages. Grafakos et al. (70) and Wang et al. (69) had a robust assessment, incorporating organizational dimension as a requirement for resilience with multiple indexes. Faber et al. (79) introduced a hierarchical governance system, considering regulations, hazards, and resources at different levels. Consequently, despite these studies having heterogeneous characteristics, a good starting point to propose an exhaustive framework that evaluates all these characteristics would be to converge the best features, parameters, and techniques applied by each of them, where possible.

3.4 Theoretical analysis of an integrated assessment

Addressing the second research question (What are the opportunities and challenges of an integrated resilience and sustainability assessment method for CI?), this subchapter delves into the opportunities and challenges of an integrated approach for assessing both resilience and sustainability. It examines potential threats and benefits entailed in this endeavor, drawing insights from existing reviews (1,3,76,80–84) that have explored this subject. To gain a comprehensive perspective, a Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis was conducted to pinpoint the strengths, weaknesses, opportunities, and threats associated with the integration of resilience and sustainability for CIs. Figure 7 visually represents the allocation of characteristics within each category.

The integrated approach of resilience and sustainability offers several strengths and opportunities. It provides a comprehensive approach that enhances decision-making by understanding vulnerabilities, risks, and potential impacts on CI systems. The interdisciplinary nature of this approach fosters increased engagement and inclusivity among stakeholders, resulting in more participatory decision-making. Moreover, the systemic perspective considers interconnections, interdependencies, and external factors such as climate change and economic conditions.

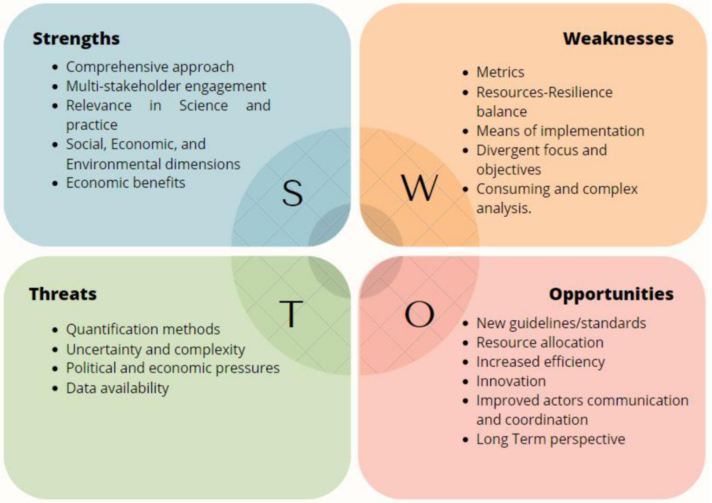

Figure 7. SWOT analysis for integrated resilience and sustainability approach, based on (1,3,76,80–84).

Integrating resilience and sustainability assessments leads to economic benefits, including reduced infrastructure maintenance costs, improved productivity, and increased competitiveness. This, in turn, contributes to overall economic growth and development. Furthermore, the relevance of an integrated approach is evident in global agendas, new standards, and sustainability certifications, highlighting the need to address resilience and sustainability simultaneously. The integration of these assessments promotes innovation by developing solutions that enhance the resilience and sustainability of CI, such as renewable energy sources and smart grid technologies.

Improved communication and coordination among stakeholders are facilitated through the integrated approach, although challenges may arise due to diverse perspectives, priorities, and expertise. Addressing the long-term perspective requires defining common time horizons that align with the desired resilience and sustainability goals of critical infrastructure. Lack of data, uncertainties, and complexities of assessing resilience and sustainability pose threats, affecting the validity and reliability of assessments.

Political and economic pressures may prioritize short-term goals over long-term resilience and sustainability objectives, leading to conflicts of interest and biased assessments. Quantification methods used for resilience and sustainability differ, with sustainability often relying on checklists and inquiries, while resilience employs performance indicators and loss performance formulas. To overcome these threats, multidisciplinary approaches involving experts from different fields and collaboration with stakeholders are necessary. The use of various methods, accurate data, and transparency regarding assumptions, limitations, and uncertainties should be emphasized.

The weaknesses of an integrated approach include the need for common metrics within the complexity of comprehensive approaches, that reconcile the distinct assessment goals and focuses of resilience and sustainability. The balance between efficiency and resilience in CIs can conflict but can be overcome by designing systems that increase resilience while reducing resource consumption and environmental impacts (Faber et al., (79)). Sustainability aims to reduce impacts and resource overconsumption, while resilience focuses on preparing for and adapting to disruptions. Its implementation involves improving environmental protection and reducing social and economic impacts for sustainability, and testing CIs' performance in adaptation and recovery for resilience.

In the future, resilience and sustainability assessments should be integrated rather than conducted separately. Separate studies for CI are common, but they can lead to inconsistent answers and conflicts between resilience and sustainability solutions. Integration is supported by existing standards, agendas (see sections 1.2 and 1.3), and studies that assess CI resilience and sustainability. Global agendas, such as the Sustainable Development Goals, promote the integration of these areas. An integrated study offers strengths and opportunities by linking multiple entities in a robust analysis, providing economic benefits, and reducing social and environmental generated impacts more efficiently. Therefore, future studies should explore joint assessments of resilience and sustainability to optimize infrastructure and address potential conflicts.

In order to provide guidance for future research and address the existing gaps in the literature, the fourth research question underlying this article (What are the gaps and limitations in the existing research?) must be addressed, emphasizing the essentiality of integrating resilience and sustainability in CI assessment. Despite the presence of some international standards, promising results have been derived from the analysis of twelve selected studies.

One critical gap is identified concerning the insufficient evaluation of environmental and social impacts. Current methodologies tend to narrowly focus on quantifying CO2 emissions, while overlooking a broader spectrum of effects. Social assessments predominantly center on direct impacts, failing to encompass the socioeconomic, educational, health, and life expectancy implications of CIs. Additionally, the oversight of society's readiness to cope with resilience-enhancing measures is noted.

The area of governance, another frequently disregarded aspect, assumes a pivotal role in CI management and resilience. The efficiency and adaptability of infrastructure systems are influenced by effective governance due to the close connection between infrastructure management and social capacity. Recognizing the influence of external boundary conditions and infrastructure governance on the risks associated with natural hazards is deemed vital.

Furthermore, existing integrated studies often narrow their focus to single hazards and specific contexts, thus limiting their applicability as general tools for resilience assessment. To address this gap, an adaptable infrastructure resilience assessment framework should be developed, aiming to provide a consistent approach for making resilience investment decisions. Nevertheless, it is essential to acknowledge the resource-intensive and complex nature of integrated assessments, which may present challenges to both researchers and stakeholders.

Lastly, to address the fifth research question (How can future research close the existing research gaps?), some indications are given further. First, the necessity of incorporating comprehensive indicators within future studies needs to be highlighted. These indicators should encompass economic, environmental, and social impacts, including factors such as socioeconomic well-being, education, health, and life expectancy. Additionally, the integration of governance aspects, proactive and reactive resilience measures, and comprehensive life cycle assessments is imperative. Moreover, researchers should investigate the correlations between variables throughout the CI life cycle, all while considering the unique constraints and limitations of their specific contexts.

In summary, this study offers valuable guidance and suggestions for future research endeavors aimed at developing integrated methodologies. Regardless of the chosen approach, researchers must ensure that indicators comprehensively evaluate environmental and social impacts. This comprehensive evaluation should not only account for direct impacts on functionality, services, and event victims but also encompass the broader effects of CIs on socioeconomic well-being, education, health, and life expectancy. The inclusion of governance aspects, encompassing management plans, maintenance, and emergency response, is vital for resilience assessment across the infrastructure's life cycle. Effectively assessing the entire life cycle requires an analysis of potential risks and the implementation of proactive and reactive measures. Furthermore, in cases where the proposed methodology lacks a unified measure of sustainability and resilience, conducting correlation analyses between variables can elucidate their interdependencies. Importantly, researchers should apply these guidelines while recognizing the unique constraints and limitations of their individual research contexts.

4 CONCLUSIONS

The demand for aligning agendas to unite seminal international guiding frameworks in sustainability (SDG), built environment (UN-HABITAT Agenda), and disaster risk (SFDRR) has been widely acknowledged. However, there remains a lack of unified frameworks and methods. Both the Sendai Framework and SDG necessitate indicators for measuring resilience and sustainability, creating an opportunity for further alignment and method integration. While sustainable development has gained importance, the integration of sustainability with resilience assessment frameworks has been a gradual process.

The examination of existing literature and the analysis of twelve selected studies have allowed us to shed light on the importance of integrating resilience and sustainability assessments in CI evaluation. This systematic review has identified emerging concepts, frameworks, and methodologies that integrate resilience and sustainability assessments, highlighting both the opportunities and challenges they present. Furthermore, through this research, critical gaps and limitations that warrant attention and action in the field were identified. These findings underscore the need for significant changes and improvements in the way we approach CI assessment, particularly in acknowledging the comprehensive nature of impacts and risks.

This research has revealed that the current methodologies in place often inadequately address environmental and social impacts, focusing primarily on quantifying CO_2 emissions and direct consequences. These shortcomings demonstrate a clear need for a more holistic perspective, one that considers a broader spectrum of effects, including socioeconomic well-being, education, health, and life expectancy. Moreover, our analysis has underscored the importance of evaluating society's readiness to cope with measures aimed at enhancing resilience against hazards.

The impact of this new knowledge extends beyond the research community. It has the potential to bring about significant changes in the functioning of the entire system, particularly in CI management and resilience enhancement. Recognizing the role of governance, as influenced by external boundary conditions and infrastructure governance, in shaping the risks associated with natural hazards becomes vital for more effective and adaptive infrastructure systems.

The values and contributions added by this research are multifaceted. By addressing the identified gaps and limitations, this study offers a path toward more robust, resilient, and sustainable CI systems. It highlights the importance of comprehensive indicators, governance scrutiny, proactive and reactive resilience measures, and a broader hazard analysis in evaluating CI throughout its life cycle.

Looking forward, future research endeavors should capitalize on these findings and strive to incorporate comprehensive indicators in their studies. These indicators should encompass economic, environmental, and social impacts, along with governance aspects, proactive and reactive resilience measures, and comprehensive life cycle assessments. Researchers should explore correlations between variables throughout the CI life cycle, all while considering the unique constraints and limitations of their individual research contexts.

To conclude, this research has provided not only insights into the current state of integrated resilience and sustainability CI’s assessment but also a roadmap for future improvements. The identified gaps and limitations serve as a call to action for researchers, practitioners, and policymakers to collaborate and develop more integrated and adaptable assessment frameworks. These frameworks, despite their resource-intensive nature, hold the potential to enhance system resilience, and sustainability. As the field continues to evolve, the impacts of this research on the CI landscape will become increasingly evident, ultimately contributing to a safer and more resilient future for critical infrastructure systems.

5 DECLARATION AND STATEMENTS

Data availability statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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Disclosure statement

The authors report there are no competing interests to declare.

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