Comprehensive Analysis of Sustainability Rating Systems for Road Infrastructure

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Review

Comprehensive Analysis of Sustainability Rating Systems for Road Infrastructure

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Abstract: Sustainability rating systems (SRSs) have emerged as indispensable frameworks for advancing the environmental, social, and economic sustainability of road infrastructure. Despite their growing adoption, their integration as authoritative tools within infrastructure planning and development remains limited. This study provides a comprehensive evaluation of eight leading SRSs—CEEQUAL, Greenroads, GreenLITES, GreenPave, I-LAST, INVEST, BE2ST-in-Highways, and Envision—focusing on their structural frameworks, criteria weightings, adherence to the three pillars of sustainability, and alignment with international benchmarks such as ISO, EN, and ASTM standards. By considering the three pillars of sustainability, the analysis of the eight SRSs reveals a disproportionate focus on environmental well-being (43%) and social well-being (42%), with economic well-being receiving minimal emphasis (15%). Furthermore, this study identifies notable deficiencies in the integration of critical international standards, including ISO, EN, and ASTM, which constrains the comprehensiveness and global applicability of these frameworks. Key findings suggest that the current SRSs inadequately address the principles of a circular economy, risk management, and social equity, highlighting areas for methodological enhancement. This review offers critical insights for researchers, policy makers, and practitioners seeking to refine sustainability rating systems for road infrastructure. By consolidating existing knowledge and proposing methodological advancements, this study contributes to the evolution of SRSs into comprehensive, globally relevant tools for sustainable infrastructure development.

Keywords: sustainability rating systems (SRSs); infrastructure sustainability; life cycle assessment (LCA); ISO; EN; ASTM standards; circular economy; sustainable development

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1. Introduction

Transportation infrastructures, such as roads, railways, airports, and ports, play a crucial role in the social development and economic growth of a country. Among them, roads are the most diffused worldwide, as they allow the highest degree of flexibility in the mobility of people and goods. Moreover, with the advent of the age of smart cities and infrastructures, the current undeniable relevance of roads in overall mobility is poised to grow further [1–3]. To comply with the underlying concepts of smart infrastructures, key features of the "new generation roads" will be digitalization as well as sustainability [2,4].

The sustainability of either smart or traditional roads is attracting an ever-increasing interest in the research community. However, although sustainability is not a new topic in the transportation infrastructure field, a significant gap still exists in the identification and quantification of best practices [5–7]. Sustainability relies on three main interconnected pillars, which are environmental [8–10], social, and economic well-being. Such an intrinsic multi-disciplinary character makes an overall assessment of the sustainability of infrastructural projects a challenging task [4,6]. In response to the need for a practical assessment methodology, several independent sustainability rating systems to be used for transportation infrastructures have been developed in recent years [7,11,12]. In the following, a historical overview of the most relevant rating systems is provided, with details related to their geographical and temporal collocation, as well as details related to the field of applicability [11,13,14] (Figure 1 and Table 1).

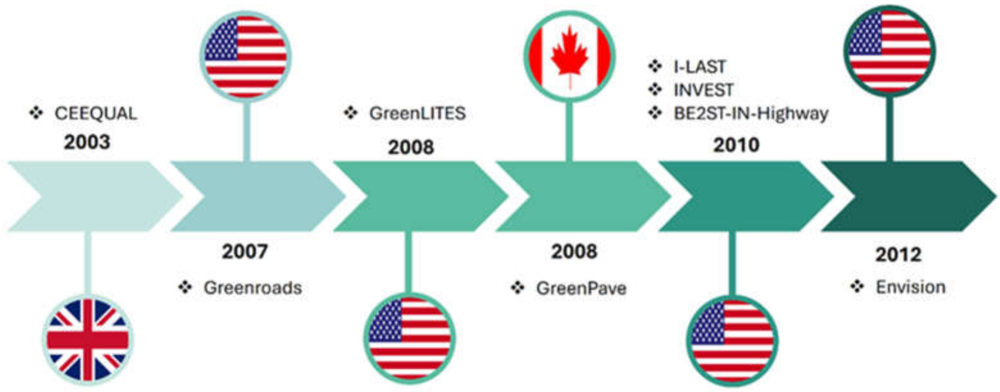

Figure 1. SRS timeline history.

Table 1. Introduction to the examined rating systems.

SRS	Full Name	Origin	Project Stage
CEEQUAL V6 (2020)	Civil Engineering Environmental Quality Assessment and Award Framework	Institute of Civil Engineering (UK)	Design Construction
Greenroads V2 (2019)	Green roads	University of Washington (USA)	Design Construction
GreenLITES V2.1.0 (2010)	Leadership In Transportation Environmental Sustainability	New York State Department of Transportation (USA)	Design Operation
GreenPave V2.1 (2017)	Green Pavement	Ontario Ministry of Transportation (Canada)	Construction Reconstruction Rehabilitation
I-LAST V2.02. (2021)	Illinois Livable and Sustainable Transportation	Illinois Department of Transportation (USA)	Design Construction Operations Maintenance
INVEST Manual Guide (2016)	Infrastructure Voluntary Evaluation Sustainability Tool	Federal Highway Administration, Washington (USA)	Design Construction Operations Maintenance
BE2ST-in-Highways We-access (2023)	Building Environmentally and Economically Sustainable Transportation–Infrastructure–Highway	University of Wisconsin–Madison (USA)	Design
Envision Manual Guide (2015)	Envision	Institute for sustainable Infrastructure, Washington (USA)	Design

The first rating system applicable to the specific field of road infrastructure was developed by the Institution of Civil Engineers (ICE) in the United Kingdom. Known as

CEEQUAL [15], it is an assessment and award system that can be used to evaluate all forms of civil engineering, infrastructure, landscaping, and public realm projects and contracts. In 2003, the methodology was open to the public, and after a series of modifications and upgrades also dedicated to the widening of the field of applications, in 2015, it became part of the Building Research Establishment environmental assessment method (BREEAM) [16]. In its actual version, it is divided into CEEQUAL for projects and CEEQUAL for term contracts. The field of applicability of CEEQUAL for projects includes transportation infrastructures such as highways, railways, and ports; specialized projects like demolition or remediation work; and other infrastructural projects such as wind farms, flood-relief plans, wastewater treatment facilities, and utilities. On the other hand, CEEQUAL for term contracts mainly focuses on the maintenance activities of infrastructure networks and assets.

In 2007, Greenroads [17] was developed at the University of Washington in the United States. Greenroads aims to honor and reward road design and construction projects that show significant improvements in sustainability performance in comparison to contemporary common practices [18,19]. After its first inception, Greenroads methodology was subjected to successive modifications, which gave rise to various versions that stem from the prominent collaboration between the University of Washington and the CH2M HILL consultant company. Further contributions were provided by several industrial groups and consultants, which supported the development of the rating system through pilot projects, case studies, and commentary [13,18].

In 2008, the New York State Department of Transportation (NYSDOT) launched a project design certification program called GreenLITES [20,21], the result of a long-term commitment of the NYSDOT to the sustainability analysis and improvement of transportation projects. GreenLITES is a self-certification process that discriminates against projects considering the level of sustainability implemented in the design choices. This rating program is intended as an internal management tool of NYSDOT that can be used for self-evaluating current performances, highlighting best practices as well as identifying specific areas for improvement in transportation projects [5,11].

In 2010, three new methodologies, with distinct targets and application areas, were implemented in North America: I-LAST [22], INVEST [23], and GreenPave [19].

The I-LAST (Illinois Livable and Sustainable Transportation) rating system and guide arose from the cooperation among the Illinois Department of Transportation, the American Council of Engineering Companies, and the Illinois Road and Transportation Builders Association. This method focuses on highway projects, and its potential use is decided, on a voluntary basis, by the agency that commissions the work.

The INVEST (infrastructure voluntary evaluation sustainability) tool was conceived by the Federal Highway Administration to assist US State Departments of Transportation, metropolitan planning organizations, local transportation agencies, and other transportation professionals in evaluating and enhancing the sustainability of transportation plans, projects, and programs [11,12]. It is a voluntary, self-directed, and free web application that can support the decision-making process during planning, operation, and maintenance activities.

The GreenPave sustainability rating system was developed in Ontario, Canada. It is a simplified rating system inspired by LEED (leadership in energy and environmental design) and GreenRoads that assesses the sustainability of new reconstruction and rehabilitation projects. The key distinction between GreenPave and other sustainability evaluation techniques is that GreenPave is completely focused on pavement structures [6,19].

In 2012, the BE2ST-in-Highways [24] (building environmentally and economically sustainable transportation-infrastructure-highways) arose from the cooperation between the Wisconsin Department of Transportation and the University of Wisconsin–Madison in the United States. This rating system focuses on the planning and designing stages of highway construction, with the specific purpose of implementing sustainability goals in the infrastructural project.

In the same year, the Envision [25] sustainability rating system was developed in collaboration between the Zofnass Program for Sustainable Infrastructure at the Harvard University Graduate School of Design and the Institute for Sustainable Infrastructure (ISI) [8,25] in the United States. The Envision system is focused on physical infrastructures, including all civil, energy, and transportation infrastructure types, and it addresses all stages of a project's life cycle, including planning, design, construction, operation, and end of life [24,26]. The Envision system allows a rating of infrastructural projects based on their overall contribution to the three pillars of sustainability.

This review paper aims to analyze and compare the most widespread sustainability rating systems in the sector of road infrastructure. Through a thorough examination of category and indicator weightings, adherence to the triple bottom line, and life cycle considerations, this study aims to provide valuable insights into the functioning, suitability, and associated benefits or drawbacks of the available methodologies [4,7,27]. By focusing on these crucial features, this research endeavors to contribute to the understanding of the role played by environmental, social, and economic criteria in the development of more sustainable roadways [5,9].

Background

General Structure of SRSs

All the SRSs analyzed in the present study are organized into several categories, selected by each agency in accordance with the specific criteria used for the quantification of sustainability. These categories differ from system to system in terms of both number and type, thus inevitably leading to macroscopic differences in the outcomes of the rating performed according to each procedure.

In the following, the number of categories and a list of all the categories considered in each method are briefly presented:

- CCEQUAL: 9 categories—management, resilience, communities and stakeholders, land use and ecology, landscape and heritage environment, pollution, resources, transport networks, and innovation [15];
- GreenRoads: 6 categories—environment and water, construction activities, material and design, utilities and control, access and livability, creativity, and effort [17,18];
- GreenLITES: 20 categories—alignment selection, context-sensitive solutions, land use and community planning, protect/enhance/restore wildlife habitat, protection/mitigation for removal of trees and plants communities, stormwater management, best management practices, reuse of materials, recycled content, local materials, bio-engineering techniques, hazardous material minimization, improve traffic flow, reduced electrical and petroleum consumption, improve bicycle and pedestrian facilities, noise abatement, stray light reduction, and innovation [20,21];
- GreenPave: 14 categories—long-life pavement, permeable pavement, noise mitigation, cool pavement, recycled content, undisturbed pavement structure, local materials, quality of the construction, reduced energy consumption, reduction in greenhouse gas emissions, pavement smoothness, pollution reduction, innovation in design, and exemplary process [19];
- I-LAST: 9 categories—planning, design, environmental, water quality, transportation, lighting, materials, innovation, and construction [22];
- INVEST: 33 categories—economic analysis, LCCA, context-sensitive project development, highway and traffic safety, educational outreach, tracking environ-

mental commitments, habitat restoration, stormwater quality and flow control, ecological connectivity, pedestrian and bicycle facilities, transit and High Occupancy Vehicles (HVO) facilities, freight mobility, Intelligent Transportation Systems (ITSs) for systems operations, historical/archeological/cultural preservation, scenic/natural/recreational qualities, energy efficiency, maintenance and irrigation of vegetation, reuse/repurposes/recycling of materials, earthworks balance, long-life pavement, reduction in emissions in pavement materials, permeability of pavement, construction environmental training, reduction in the emission of construction equipment, mitigation of construction noise, construction quality control plan, construction waste management, low-impact development, infrastructure resiliency planning and design, light pollution, and noise abatement [23];

- BE2ST-in-Highways: 9 categories—social carbon cost, traffic noise, Global Warming Potential (GWP), in situ recycling rate, hazardous waste, water consumption, total recycled material, LCCA, and energy consumption [24];
- Envision: 5 categories—quality of life, leadership, resource allocation, natural world, climate, and risk [25].

It can be observed that several categories are common in different SRSs. However, it must be highlighted that some of these common SRS categories refer to specific fields of application and scopes that can vary among the different methodologies. By way of example, the "management" category in CEEQUAL focuses on project management and stakeholder engagement, GreenLITES refers to aspects like stormwater management and best management practices aimed at minimizing environmental impacts and improving operational efficiency, while in INVEST, the management category is specifically related to construction waste.

Another common category is represented by "land use", which covers the planning and development of land aiming to preserve natural habitats in CEEQUAL while emphasizing the integration of infrastructure projects with community and environmental needs in GreenLITES.

The issue of pollution is tackled by CEEQUAL, which addresses general pollution concerns. GreenPave introduces a specific "pollution reduction" category, specifically focused on the potential for minimizing pollutants through a project [19], while INVEST considers "light pollution", thus aiming to reduce excessive artificial light that can affect ecosystems and human health.

The "resources" category is recognized by both CEEQUAL, which includes "resources" as a criterion for the sustainable use of materials and energy, and Envision, which focuses on "resource allocation", thus evaluating whether resources are efficiently and equitably used. The focus on the environment and water is evident in Greenroads, which addresses environmental protection and water management. I-LAST deals with "environmental" and "water quality", emphasizing pollution prevention and water conservation. In INVEST, "construction environment training" highlights educating workers on sustainable construction practices to minimize environmental impacts.

In terms of construction, various activities are highlighted across the analyzed SRSs. Greenroads discusses "construction activities", focusing on the environmental and community impacts of construction processes, while GreenPave covers "construction quality", ensuring that projects will meet high standards for durability and environmental performance. Moreover, INVEST addresses a range of issues, including "construction equipment emission reduction", "construction noise mitigation", "construction quality control plan", and, as already mentioned above, "construction waste management". All these categories are aimed at reducing the negative environmental impacts associated with construction operations. Finally, I-LAST broadly addresses "construction", covering general construction practices.

The "material" category includes various subcategories across the SRSs. Greenroads mentions "material and design", focusing on the sustainable selection and use of materials. GreenLITES discusses "reuse of materials", "local materials", and "hazardous material minimization", promoting the use of recycled and local materials and reducing hazardous substances. GreenPave addresses "local materials", encouraging the use of regionally sourced materials to reduce transportation emissions. INVEST introduces categories like "reduce, reuse, and repurpose material", "recycle materials", and "reduced energy and emissions in pavement materials", focusing on a sustainable life cycle of materials. I-LAST simply refers to "materials", and BE2ST-in-Highways includes "total recycled material", promoting the use of high quantities of recycled materials in projects.

The issue of noise is explicitly addressed by five of the eight SRSs. GreenLITES includes "noise abatement", focusing on the reduction in noise pollution in urban areas. GreenPave addresses "noise mitigation", aiming at minimizing the noise generated by roadways. INVEST examines "construction noise mitigation" and "noise abatement", focusing on the reduction in noise during and after construction. BE2ST-in-Highways also addresses this concern under the category of "traffic noise", emphasizing the reduction in noise pollution from traffic.

Lastly, innovation is also included as a category with a wide scope of applications in CCEQUAL, GreenLITES, and I-LAST, while in GreenPave, it is specifically related to the design stage of a project.

These overlapping categories illustrate similarities among the criteria selected by different SRSs to quantify the sustainability level of road infrastructures, which emphasize overall management, environment, resource use, and innovation in sustainable construction practices [15,18,23,24].

It is worth noticing that there is a strong variation in the specificity and level of detail of categories across different SRSs. For instance, some systems provide very detailed categories, such as INVEST's "Site Vegetation, Maintenance, and Irrigation", which clearly defines quite specific activities and outcomes for sustainable vegetation management. In contrast, other systems use more general terms like I-LAST's "Environmental" or "Materials", which can encompass a broad range of aspects but lack specificity. Similarly, CEEQUAL includes a broad "Management" category, whereas GreenLITES details specific areas like "Stormwater Management (Volume & Quality)" and "Best Management Practices (BMPs)", focusing on particular aspects of management. This difference in specificity can have significant implications. Highly detailed categories provide clear guidance and measurable criteria, making it easier to assess compliance and performance. They also help in setting clear objectives for specific sustainability practices. On the other hand, broader categories offer more flexibility but can lead to ambiguity in interpretation and implementation. This can result in challenges when evaluating projects or comparing them across different systems. Therefore, the choice between specificity and generality in categorization can influence the effectiveness of sustainability assessments and the clarity of the goals set by these systems.

2. Methodology

A robust and systematic methodology was adopted in this study to critically evaluate sustainability rating systems (SRSs) for road infrastructures [7,19]. The methodology is structured into three main components: a comprehensive assessment of SRS characteristics and their different scales of analysis, a recategorization based on both macro-impact categories and the three sustainability pillars, and an examination of alignment with international standards. Various guidelines and international standards were referenced to support these categorizations. To support the analysis and the systematic identification of indicators, NVivo 12 software [28] was employed as a qualitative data analysis tool, ensuring accuracy and consistency throughout the process.

The first part presents a detailed evaluation of the characteristics of each SRS, focusing on three main scales of analysis: road, pavement, and material [18,19]. This comprehensive assessment aims to provide a detailed understanding of how each SRS addresses critical sustainability factors across these different scale levels of analysis [5,12].

The second part of this study involves a rigorous analysis of the SRS categories, followed by their recategorization under both macro-impact categories and the three core pillars of sustainability: environmental well-being, social well-being, and economic well-being [4,8]. In alignment with the Global Guidance on Environmental Life Cycle Impact Assessment Indicators (2016) and other environmental indications, credits related to climate change, energy consumption, land use, water resources, and quality improvements were classified under the environmental pillar [9]. Social-related indicators were identified and isolated based on the Guidelines for Social Life Cycle Assessment of Products and Organizations 2020, which define 40 subcategories for assessing social well-being. Conversely, metrics involving performance, recycled and recovered materials were assigned to the economic pillar due to their relevance in promoting resource efficiency and consequent cost savings, thereby enhancing the overall economic sustainability of the system [27]. This systematic reclassification enables a straightforward comparison and evaluation of the potential effectiveness of each methodology across the three dimensions of sustainability [6,24].

The last part of the analysis focuses on assessing the adherence of each SRS to relevant international standards, specifically ISO, EN, and ASTM standards related to road infrastructure sustainability [15,29,30]. This examination involves the identification of which international standards are incorporated within each SRS methodology, and it is followed by a gap analysis aimed at identifying and analyzing areas where specific standards are currently not addressed [31,32]. This allows a first assessment of the alignment of each SRS to well-established international benchmarks and a subsequent evaluation of potential improvements stemming from the integration of these standards in the SRS frameworks [15,33].

3. Results and Discussion

3.1. Assessment Characteristics

Certification methodologies vary widely among the systems because of diverse objectives and needs that can stem from different geographical areas and time periods in which each SRS was established. CEEQUAL employs a comprehensive rating system with categories such as “management”, “resilience”, and “communities and stakeholders”, among others, each weighed differently to contribute to a total score of 5500 points. In contrast, GreenRoads utilizes a simpler framework with categories like “environment and water” and “material and design”, assigning maximum credits totaling 130. GreenLITES, with its own set of categories, such as “reuse of materials” and “improved traffic flow”, provides a total of 279 credits. GreenPave is characterized by a simpler framework, focusing on specific pavement-related aspects like “long-life pavement” and “recycled content”, totaling 32 credits. The I-LAST assesses “planning”, “design”, and “environmental factors” among others, with a total of 300 credits. The INVEST system evaluates categories like “energy efficiency” and “infrastructure resiliency planning”, with a total of 169 credits. Envision, finally, has a broader scope with categories such as “quality of life” and “natural world”, contributing to a total of 809 credits.

BE2ST-in-Highways uses a more generalized approach composed of broader categories, emphasizing aspects like "social carbon cost" and "energy consumption". The assessment types for these systems are predominantly third-party evaluations, ensuring impartiality and consistency. The scope of these assessments varies, addressing project development, design, and sometimes operation. For example, CEEQUAL, GreenPave, INVEST, Envision, and BE2ST-in-Highways focus on project development, while GreenLITES includes project design in its scope, and GreenRoads exclusively incorporates project operation.

Rating classifications across the systems generally adopt an Olympic-style scheme such as Gold, Silver, Bronze for BE2ST-in-Highways; Platinum/Trillium Platinium/Evergreen, Gold, Silver, Bronze for I-LAST, INVEST, Envision, GreenPave, GreenRoads, and GreenLITES; and CEQUAL adopts as award grades Outstanding, Excellent, Very Good, Good, Pass, Unclassified.

This diversity in classification approaches underscores the different priorities and methodologies among the SRSs, emphasizing the importance of selecting the most appropriate system based on specific project needs. In summary, the detailed analysis of these SRSs illustrates their unique origins, certification methods, and assessment approaches. The variety in their criteria, scoring, and rating classifications highlights the need for careful selection based on the specific sustainability goals and requirements of a project. Typically, a score that contributes to the definition of the final assessment is assigned to each category.

The allocation of points within various sustainability rating systems (SRSs) can be indicative of the priorities and focus areas of each system. These scores are typically determined using a mix of qualitative and quantitative methods, reflecting both the subjective judgments of experts and measurable objective criteria.

Table 2 summarizes the award grades used for rating classification and the categories to which the highest and lowest scores are assigned for each SRS.

Table 2. The magnitude of the weight of the most/least categories in SRSs.

SRS	Award Grades	Total Points	Highest-Score Category	Points	Lowest-Score Category	Points
CCEQUAL	Outstanding, Excellent, Very Good, Good, Pass, Unclassified	5500	Resources	1450	Pollution/Transportation network	400
GreenRoads	Evergreen, Gold, Silver, Bronze	130	Environment and water	30	Creativity and effort	15
GreenLITES	Evergreen, Gold, Silver, Certified	279	Improve bicycle and pedestrian facilities	35	Stray light reduction	3
GreenPave	Trillium Gold, Silver, Bronze	32	Recycled content	21	Pavement smoothness/Pollution reduction	2
I-LAST	Platinum, Gold, Silver, Bronze	300	Environmental	52	Innovation	3
INVEST	Platinum, Gold, Silver, Bronze	169	Reuse and repurpose of materials/ Infrastructure resiliency planning and design	12	Construction environmental training	1
BE2ST-IN-Highways	Gold, Silver, Bronze	100	Same magnitude for each of the nine categories	33	Same magnitude for each of the nine categories	33
Envision	Platinum, Gold, Silver, Bronze	809	Natural world	203	Leadership	121

It can be observed that the most important categories across these systems often focus on broader, holistic elements such as "resources" in CEEQUAL, "environment and water" in GreenRoads, and “natural world” in Envision. These categories tend to encompass a wide range of sustainability considerations, suggesting a comprehensive approach to environmental stewardship and resource management. Conversely, categories for which a lower score is assigned, such as “pollution/transportation network” in CEEQUAL or “creativity and effort” in GreenRoads, often represent more specific or narrower aspects of sustainability. This might indicate that these systems prioritize overall environmental and resource impacts over more specialized or niche considerations.

Each rating system emphasizes different aspects of sustainability based on its primary focus. CEEQUAL, with a total of 5500 points, prioritizes “resources”, highlighting the efficient use and management of materials, energy, and water. The lesser emphasis on “pollution/transportation network” suggests these factors are considered less critical within the broader context of sustainability. GreenRoads places the greatest importance on “environment and water”, reflecting a strong focus on ecological health and water management. While innovative solutions are valued, as indicated by the relatively lower emphasis on “creativity and effort”, they are not the system’s primary concern. GreenLITES prioritizes “improve bicycle and pedestrian facilities”, demonstrating a commitment to enhancing sustainable transportation options and urban mobility. In contrast, less importance is given to “stray light reduction”, suggesting that light pollution, though acknowledged, is secondary to transportation infrastructure. GreenPave emphasizes “recycled content”, underscoring a commitment to using recycled materials in construction and adhering to the circular economy principles. The lesser focus on “pavement smoothness/pollution reduction” indicates these aspects are considered secondary benefits rather than primary goals. INVEST highlights “reuse and repurposing of materials/infrastructure resiliency planning and design”, focusing on sustainability through resource efficiency and resilient infrastructure. The reduced emphasis on “construction environmental training” suggests that while education and training are important, they are not the central driver of the system’s sustainability objectives. I-LAST’s focus on “environmental” categories reflects a broad commitment to environmental considerations, with less emphasis on “innovation”, potentially indicating a preference for established methods over novel approaches. Envision prioritizes the “natural world”, emphasizing the preservation and enhancement of natural ecosystems. The lower emphasis on “leadership” implies that while leadership in sustainability is valued, the practical aspects of environmental protection are prioritized. Finally, BE2ST-in-Highways adopts a balanced approach by giving equal weight to each category, indicating that all aspects of sustainability are considered equally important. Overall, these variations in the emphasis of categories reflect the unique objectives and methodologies of each SRS. The prioritization of broader, more encompassing categories like “resources” or “environment” suggests a holistic approach, while systems that highlight specific categories like “recycled content” or “improve bicycle and pedestrian facilities” may target particular sustainability outcomes or challenges.

3.2. Road, Pavement, and Material Scales of Analysis

From an examination of the general scope and specific aims set by each SRS in the definition of the assessment indicators, different scales of analysis can be identified to prioritize sustainability features of infrastructures. The three main scales adopted in SRS methodologies refer to a road level, a pavement level, and a material level (Table 3).

Table 3. Summary of SRS indicators acting on a road, pavement, or material scale.

SRS	Road	Pavement	Material
CEEQUAL	Road safety Risk reduction for vulnerable users	-	-
GreenRoads	Roadway safety Road construction noise Road maintenance	Pavement management system Pavement reuse Long-life pavement Permeable pavement Cool pavement Quiet pavement Pavement performance tracking	Warm mix asphalt technology Porous asphalt
GreenLITES	Traffic flow improvement	Reuse of material Recycle content	Reuse of material Hot mix asphalt recycling Reduction in petroleum consumption
GreenPave	Road traffic noise	Long-life pavement Permeable pavement Cool pavements Undisturbed pavement structure Pavement smoothness	Asphalt surface treatments Permeable pavement Noise mitigation Reclaimed asphalt pavement (RAP)
I-LAST	Impervious area reduction Noise abatement by vehicle	Pavement reuse Reduction in noise levels by tinning of pavement Long-life pavement On-site recycling of pavement	Production of hot mix asphalt Hot in-place or cold in-place recycling
INVEST	Road weather management Road safety and accessibility	Long-life pavement Energy and emission reduction in pavement materials Permeable pavement Recycled material	Use recycled materials
BE2ST-in-Highways	Wildlife protection during road construction Road safety (FHWA Audit) Environmental impact characterization of road construction project	Pavement noise reduction Reusing and recycling in pavement design and construction Pavement performance analysis for rehabilitation scheduling	Recycled asphalt and Portland Cement Concrete (PCC) Traffic noise reduction
Envision	Road traffic reduction	Noise and vibration minimization	

The road scale encompasses the overall design and operational characteristics of the roadway, focusing on factors such as safety, accessibility, traffic flow, and environmental impact. For example, CEEQUAL emphasizes safety and risk reduction for vulnerable users, while GreenRoads prioritizes roadway safety, road construction noise, and maintenance. GreenLITES targets improvements in traffic flow, while GreenPave focuses on mitigating road traffic noise. Other systems like INVEST address road weather management and accessibility, and I-LAST aims at reducing impervious surfaces and vehicle noise. Envision seeks to reduce road traffic, whereas BE2ST-in-Highways includes considerations like minimizing wildlife impacts during construction and evaluating the environmental impacts of road projects. Envision seeks to reduce road traffic, whereas BE2ST-in-Highways includes considerations like wildlife protection during construction, road safety by introducing

Federal Highway Administration (FHWA) road safety audit, and environmental impacts, including environmental life cycle assessment using the PaLATE tool.

The pavement scale focuses on how design elements work together to achieve desired outcomes such as durability, longevity, and satisfactory performance. It assesses critical factors, including sustainability and noise reduction, which are inherently linked to the performance and impact of the entire pavement system rather than the properties of individual materials. GreenRoads evaluates pavement management systems, reuse of materials, long-life pavements, permeable pavements, and performance tracking. GreenLITES emphasizes material reuse and recycled content, while GreenPave includes long-life pavements, undisturbed pavement structures, and pavement smoothness. INVEST highlights long-life pavements, emission reduction in pavement materials, and the use of recycled materials. I-LAST considers noise reduction through pavement texturing, the use of recycled crushed pavement, and on-site recycling of pavement. Envision focuses on minimizing noise and vibration. BE2ST-in-Highways emphasizes reducing pavement noise and reusing and recycling materials in pavement design.

The material scale specifically evaluates the technologies used in materials production, with the greatest emphasis generally placed on asphalt. GreenRoads, for instance, assesses warm mix asphalt technology and porous asphalt. GreenLITES focuses on material reuse, recycling hot mix asphalt, and reducing petroleum consumption. GreenPave addresses the use of permeable pavements, asphalt surface treatments, and reclaimed asphalt pavement (RAP). INVEST emphasizes the use of recycled materials, and I-LAST evaluates hot mix asphalt production and the choice between hot in-place and cold in-place recycling. BE2ST-in-Highways considers the use of recycled asphalt, Portland Cement Concrete (PCC), and noise reduction technologies.

3.3. Macro-Impact Categories

Due to the high heterogeneity of the categories composing each rating system, which significantly vary in both specific subjects and numbers, the individual indicators were classified into six macro categories. These macro categories were defined as “material & resources”, “energy & emission”, “environment & water”, “construction activities”, “innovation & design”, and “access & livability”. NVivo 12 software was used to analyze each rating system to identify the described indicators and their associated credits that could fit under the defined macro categories. At the final stage, the associated weights were converted from credits to percentages, ensuring uniform scaling across different rating systems. This approach allows a straightforward comparison among methods, thus highlighting the overall emphasis placed by each SRS on different attributes of sustainability [15,19,23,25].

Figure 2 shows the relative weights of the selected macro categories in each SRS method, calculated as the relative percentage of the point scores of the indicators included in a specific category with respect to the total scoring of the rating system in question.

From an inspection of the outcomes of this comparative analysis, it can be noticed that Envision shows balanced attention to “material & resources” (23.3%), “energy & emission” (13.4%), “innovation & design” (16.7%), “environment & water” (25%), and “access & livability” (21.7%). Greenroads prioritizes “construction activities” (24.4%), “access & livability” (22.2%), and “environment & water” (22%), with a lesser focus on “material & resources” (13.3%). I-LAST emphasizes “environment & water” (34.3%), “construction activities” (21.5%), “material & resources” (10.7%), and “innovation & design” (10.7%), with moderate attention to “energy & emission” (6.9%) and “access & livability” (11.2%). GreenLITES places significant weight on “energy & emission” (38.4%), “construction activities” (29.9%), and “material & resources” (24.4%), with minimal focus on “environment & water” (7.4%) and “access & livability” (0%) [21]. INVEST exhibits a balanced distribution among "material & resources" (10.5%), "energy & emission" (5.7%), "innovation & design" (5.7%), "environment & water" (10%), "access & livability" (8.6%), and "construction activities" (2.4%). CEEQUAL concentrates on "material & resources" (9.4%), "energy & emission" (9.5%), and "environment & water" (8.5%), with no specified focus on other categories. GreenPave heavily emphasizes "material & resources" (34.4%) and "energy & emission" (25%), with a notable focus on "innovation & design" (12.5%). BE2ST-in-Highways provides an equal distribution across all six categories, with a constant weight of 16.6%.

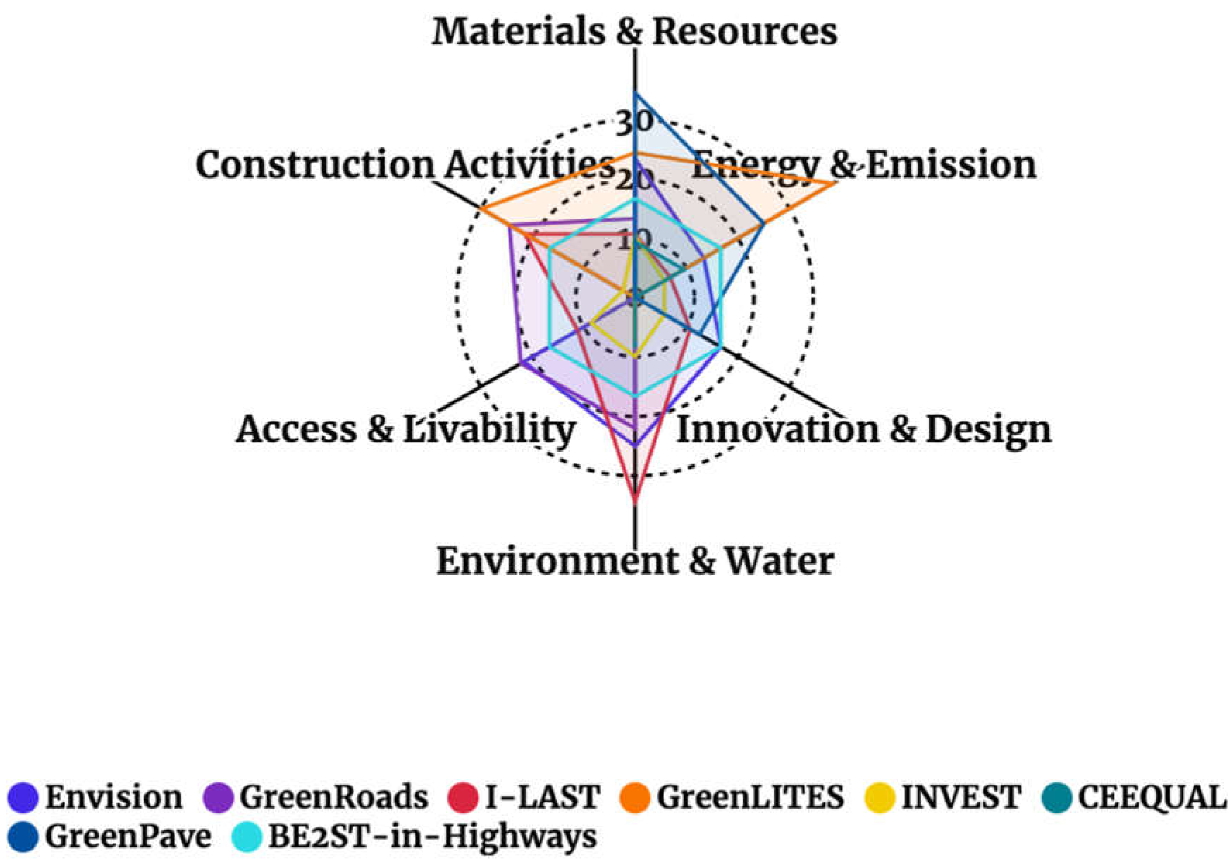

Figure 2. SRS macro categories and relative weights.

3.4. Sustainability Pillars

The concept of sustainability relies on three main pillars, which are based on the environment, society, and economy [8,9]. Although no rigid boundaries exist among these three dimensions of sustainability, the effective impacts of SRSs on each field were explored and presented in the following, analyzing the relative influence of the three pillars on sustainability ratings.

In order to minimize unavoidable overlaps due to the inherent interconnections between pillars, specific criteria derived from the available literature were adopted to allocate indicators to environmental, social, and economic well-being [34,35].

In alignment with the "Global Guidance on Environmental Life Cycle Impact Assessment Indicators" (2016), credits related to climate change, energy consumption, land use, water resources, and quality improvements are categorized under the environmental pillar [9]. Social-related indicators were identified and isolated following the "Guidelines for Social Life Cycle Assessment of Products and Organizations" [36]. In this context, social indicators reflect aspects that directly impact communities and stakeholders. Conversely, metrics involving performance and recycled and recovered materials were assigned to the economic pillar due to their relevance in promoting resource efficiency and consequent cost savings, thereby enhancing the overall economic sustainability of the system [27].

From a general overview of the results presented in Figure 3, it can be stated that sustainability assessment is generally led by environmental criteria, closely followed by social indicators, while less emphasis is commonly placed on economic targets [15,23,25]. The dominance of the environmental pillar in SRSs is also supported by the outcomes of investigations performed by Mattinzioli et al. [7]. A possible explanation for this finding comes from the fact that while economic and social requirements seem to be strongly embedded in the existing practices and local regulations of developed countries, from which these SRSs take origin, it can be inferred that environmental criteria currently represent the weakest component of sustainability in infrastructural project policies [20,22].

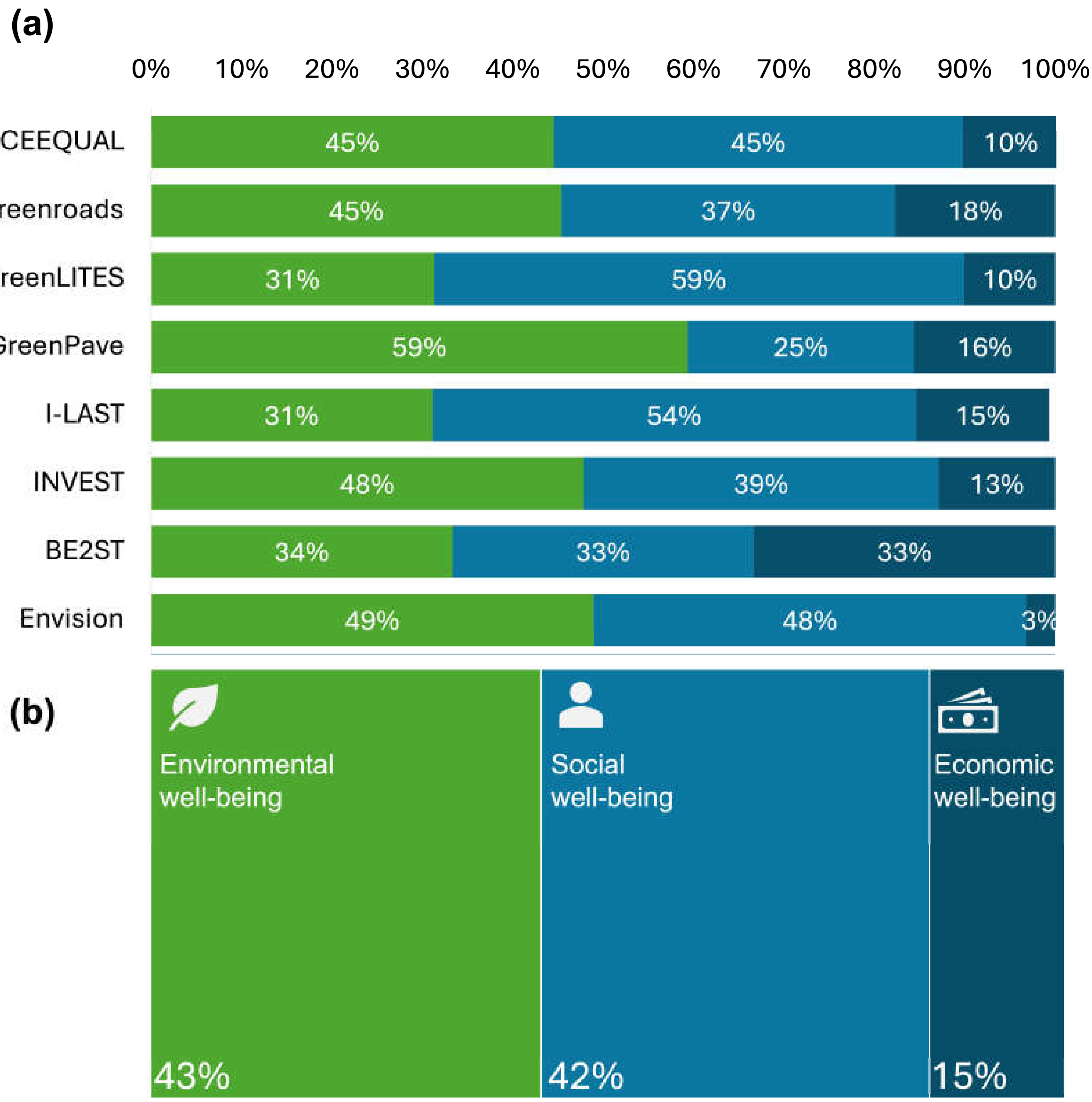

Figure 3. (**a**) Weight contribution of SRSs to three pillars of sustainability; and (**b**) average of all SRS weight contributions to three pillars of sustainability.

Inspection of Figure 3 allows a direct comparison of the relative weights that each SRS assigns to the three dimensions of sustainability. By focusing on environmental well-being, the highest weight can be found for GreenPave, with a relative percentage of 59%. This is followed by Envision (49% weight), INVEST (48% weight), CEEQUAL and Greenroads (45% weight), BE2ST-in-Highways (33% weight), and, last among rating systems, GreenLITES and I-LAST, with a contribution of 31%. When considering social well-being, the highest score is given by GreenLITES, with a total of 59%, followed by I-LAST (54% weight), Envision (48% weight), CEEQUAL (45% weight), INVEST (39% weight), Greenroads (37% weight), BE2ST-in-Highways (33% weight), and finally, GreenPave with a 25% contribution. For economic well-being, BE2ST-in-Highways has the highest contribution with 33% weight, followed by Greenroads (18% weight), GreenPave (16% weight), I-LAST (15% weight), INVEST (13% weight), CEEQUAL (11% weight), GreenLITES (10% weight), and, in last position in the overall ranking, Envision with only 3% contribution. By considering the average weight contributions from all the sustainability rating systems analyzed in the present study, the major weights of 43% and 42% were found for environmental and social well-being, respectively, while the minor contribution is related to economic well-being, with a 15% weight on the total [7].

3.5. Road Construction Sustainability Standards

The mapping of standards across the SRSs was conducted using NVivo 12 software, employing targeted search keywords for ISO, EN, and ASTM standards. This approach enabled the identification of the specific standards utilized within each SRS. Furthermore, additional international standards that could enhance the three pillars of sustainability were explored. The analysis highlighted gaps where certain relevant standards were absent within the studied SRSs, providing a basis for addressing these omissions and strengthening the comprehensiveness and applicability of sustainability assessments.

3.5.1. General Sustainability Standards

In response to the imperative for holistic sustainability in the construction industry, international standards serve as indispensable tools guiding the sector towards more environmentally, socially, and economically responsible practices. As the industry grapples with the complexities of sustainable development, standards from bodies such as the International Organization for Standardization (ISO) [29–31,37–39] and ASTM International [32] offer valuable reference points. These standards cover a wide spectrum of considerations, from building design and construction methodologies to broader community-level development strategies. By aligning with these standards, stakeholders can navigate the multifaceted challenges of sustainability, optimize resource use, and foster resilient, fair, and prosperous built environments [7]. This paper examines the pivotal role of ISO, CEN, and ASTM standards as guiding frameworks for the construction industry in its pursuit of holistic sustainability.

ISO, the International Organization for Standardization, is a global body that develops and publishes international standards to ensure quality, safety, efficiency, and sustainability across various industries. In the context of infrastructure and construction projects, ISO standards play a crucial role in providing guidelines, frameworks, and best practices to enhance the sustainability and performance of buildings, civil engineering works, and communities [30,31,37,38]. ISO 15392 [40] lays the groundwork for sustainability in building and civil engineering projects by establishing general principles. It serves as a foundational document that outlines key concepts and considerations essential for integrating sustainability into the planning, design, construction, and operation of infrastructure projects. By adhering to these principles, stakeholders can align their efforts with sustainable development goals and ensure long-term viability and resilience in their endeavors. ISO 21678 [41] complements ISO 15392 by providing a set of indicators and benchmarks specifically tailored to assess sustainability in buildings and civil engineering works. These indicators enable stakeholders to quantitatively measure and evaluate the environmental, social, and economic performance of infrastructure projects. By using standardized metrics, organizations can systematically track progress, identify areas for improvement, and demonstrate their commitment to sustainability to stakeholders and the public. Building upon the assessment framework established by ISO 21678, ISO 21931-1 [42] offers detailed guidance on improving the quality and comparability of methods for assessing the environmental performance of buildings and their external works. Additionally, ISO 15686-1 [43] provides a framework for service life planning of constructed assets, including buildings and infrastructure. It outlines general principles and processes for assessing the service life of constructed assets, focusing on factors like durability, maintenance, and performance requirements over time.

In line with the principles of a circular economy and resource efficiency, ISO 20887 [44] focuses on design for disassembly and adaptability in buildings and civil engineering works. This standard emphasizes the importance of designing infrastructure projects with future flexibility and recyclability in mind. By incorporating principles such as modular construction, material reuse, and adaptability, stakeholders can enhance the sustainability and resilience of their projects while reducing waste and environmental footprint. ISO 21929-1 [45] further expands on sustainability considerations within building construction by providing detailed guidelines and best practices. This standard addresses various aspects of sustainable construction, including materials selection, energy efficiency, and resilience to climate change. By following the recommendations outlined in ISO 21929-1, project teams can implement strategies to minimize environmental impact, enhance social benefits, and optimize overall project performance. Lastly, ISO 37101 [46] extends the scope of sustainability beyond individual projects to encompass broader community-level initiatives. This standard provides guidance on implementing management systems for sustainable development within communities, covering aspects such as infrastructure planning, land use management, and social equity. By adopting the principles and practices outlined in ISO 37101, local governments, organizations, and community stakeholders can collaborate effectively to achieve sustainable development goals, promote resilience, and enhance the quality of life for residents.

In addition to the ISO standards, the European Committee for Standardization (CEN) has developed a range of EN standards specifically tailored to the infrastructure and construction sector. EN 15643 [47] serves as a comprehensive framework for assessing the sustainability of construction works, providing guidance on evaluating various aspects such as environmental impact, resource efficiency, and social considerations. This standard enables stakeholders to systematically assess and benchmark the sustainability performance of buildings and civil engineering projects, facilitating informed decision-making and continuous improvement initiatives. Building upon the framework established by EN 15643, EN 17472 [48] focuses on the sustainability assessment of civil engineering works, offering a calculation method to quantitatively evaluate sustainability performance. By providing a standardized approach to assessing factors such as carbon footprint, resource consumption, and social impact, this standard enables project teams to identify opportunities for optimization and mitigation, enhancing the overall sustainability of civil engineering projects.

In conjunction with ISO and EN standards, ASTM, which was formerly known as the American Society for Testing and Materials, is a globally recognized organization that develops and publishes voluntary consensus standards for a wide range of industries, including construction, manufacturing, and materials, and internationally provides a comprehensive set of standards tailored to the infrastructure and construction sector, addressing various aspects of sustainability and performance. ASTM E2432 [49] serves as a foundational guide, providing principles and considerations for integrating sustainability into building design, construction, operation, and maintenance. This standard offers a holistic framework for stakeholders to face the complexities of sustainable development, emphasizing the importance of environmental stewardship, resource efficiency, and social responsibility throughout the life cycle of buildings. Complementing the overarching principles outlined in ASTM E2432, ASTM E2129 [50] offers specific guidance on the sustainability assessment of building products. This practice outlines procedures for collecting data needed to assess the sustainability of building materials and products, considering environmental, social, and economic factors. By adhering to standardized data collection methods, stakeholders can make informed decisions regarding material selection, procurement, and resource management. While the mentioned ISO, EN, and ASTM standards offer comprehensive guidelines and frameworks to promote sustainability within the construction sector, it is important to note that none of these standards are currently utilized as reference points in sustainability rating systems studies. Despite their potential to address various aspects of sustainability, such as environmental impact, resource efficiency, and social responsibility, within construction projects, their absence from existing rating systems may limit their widespread adoption and recognition within the industry [11,30,31]. Integrating ISO, EN, and ASTM standards into sustainability rating systems presents an opportunity to enhance their relevance and effectiveness in driving sustainable practices and performance within the construction sector [12]. This action would strengthen the robustness of sustainability rating systems while encouraging broader adoption of these standards as valuable tools for advancing sustainability in construction projects [11].

3.5.2. Environmental Sustainability Standards

In the realm of environmental sustainability, a robust framework of standards is essential to guide organizations towards responsible practices and measurable outcomes. At the forefront of this effort is ISO 14001 [51], which establishes the foundation for environmental management systems (EMSs). By systematically identifying, managing, and mitigating environmental impacts, organizations can not only enhance their environmental performance but also contribute to broader sustainability goals [31]. Complementing ISO 14001 are standards such as ISO 14025 [29] for environmental declaration programs and ISO 14020 [39], which establishes principles and specifies general requirements for communicating environmental aspects and impacts of products through environmental statements and programs. These standards empower consumers and stakeholders to make informed decisions, fostering sustainable consumption patterns and driving demand for environmentally responsible products and services. Furthermore, ISO 14040 and ISO 14044 [30,31] offer methodologies for conducting life cycle assessments, allowing organizations to comprehensively evaluate the environmental impacts of products, processes, or activities throughout their entire life cycle. By systematically quantifying these impacts, organizations can pinpoint areas for improvement and optimize their sustainability performance. ISO 14004 [38] provides guidelines for implementing ISO 14001, offering additional clarification and practical advice on how to establish, implement, maintain, and improve an environmental management system. In addition to product-focused assessments, ISO 14046 [37] provides guidance on water footprint evaluation, enabling organizations to manage water use and minimize environmental impact across the supply chain. Integrating these standards into environmental management systems not only enhances organizational resilience and competitiveness but also fosters a culture of continuous improvement and innovation.

Beyond specific environmental standards, the ISO 14000 series offers overarching frameworks for quality and environmental management, respectively, providing organizations with tools and guidance to drive sustainable practices across all aspects of their operations. By adhering to these standards, organizations can demonstrate their commitment to environmental stewardship, thus contributing to a more sustainable future. A diverse array of ISO standards also plays integral roles in various studied sustainability rating systems across different industries. Among them, as shown in Figure 4, ISO 14025, ISO 14020, ISO 14040, ISO 14044, and ISO 14046 are included in the CEEQUAL sustainability rating system, which focuses on infrastructure projects. Similarly, ISO 14001 and ISO 14000 features are specifically tailored for transportation projects in GreenRoads. Moreover, ISO 14004, ISO 14001, and ISO 14044, widely utilized in civil infrastructure projects, are key components of the Envision sustainability rating system. Additionally, ISO 14042, ISO 14040, and ISO 14044 take center stage in the BE2ST-in-Highways sustainability rating system, highlighting its significance in evaluating the environmental performance of highway projects. By integrating these ISO standards into their respective rating systems, organizations can effectively measure, assess, and enhance the sustainability performance of their projects across diverse sectors and industries.

Among the ISO standards that are not explicitly included in the sustainability rating systems under analysis, relevance is given to ISO 14006 [52], ISO 14067 [53], and ISO 21930 [54]. ISO 14006 emphasizes the integration of eco-design principles into environmental management systems, ISO 14067 specifically focuses on the quantification and communication of the carbon footprint of products, and ISO 21930 offers guidance on the assessment of the environmental performance of construction products. Despite their significance in promoting sustainable practices, these standards are not mentioned in sustainability rating systems, thus potentially generating a gap in formally recognizing and incentivizing organizations that prioritize eco-design and comprehensive environmental management strategies.

Within the construction sector, the European Committee for Standardization (CEN) is instrumental in advancing environmental sustainability practices. Notably, EN 15978 [55] establishes a comprehensive framework for assessing the environmental impact of buildings across their life cycle. This standard provides methodologies to calculate key environmental indicators such as greenhouse gas emissions, energy consumption, and resource depletion, offering valuable insights for sustainable decision-making in construction projects. Additionally, EN 15804 [56] focuses on environmental product declarations (EPDs) for construction products. It delineates rules and procedures for developing EPDs, which communicate the environmental performance of construction products based on life cycle assessment data. By providing transparent and standardized information about the environmental impacts of construction products, EPDs empower stakeholders to make informed decisions, thereby promoting the selection of environmentally responsible materials and products in construction projects. As shown in Figure 4, the CEEQUAL sustainability rating system, EN 15978, and EN 15804 are incorporated to enhance environmental sustainability practices within the construction sector. However, it is notable that EN 15942, which addresses principles, requirements, and guidelines for the development and communication of EPDs for construction products, is not explicitly mentioned in the sustainability rating systems studies. Such an absence highlights a gap in promoting the selection of environmentally sustainable construction products.

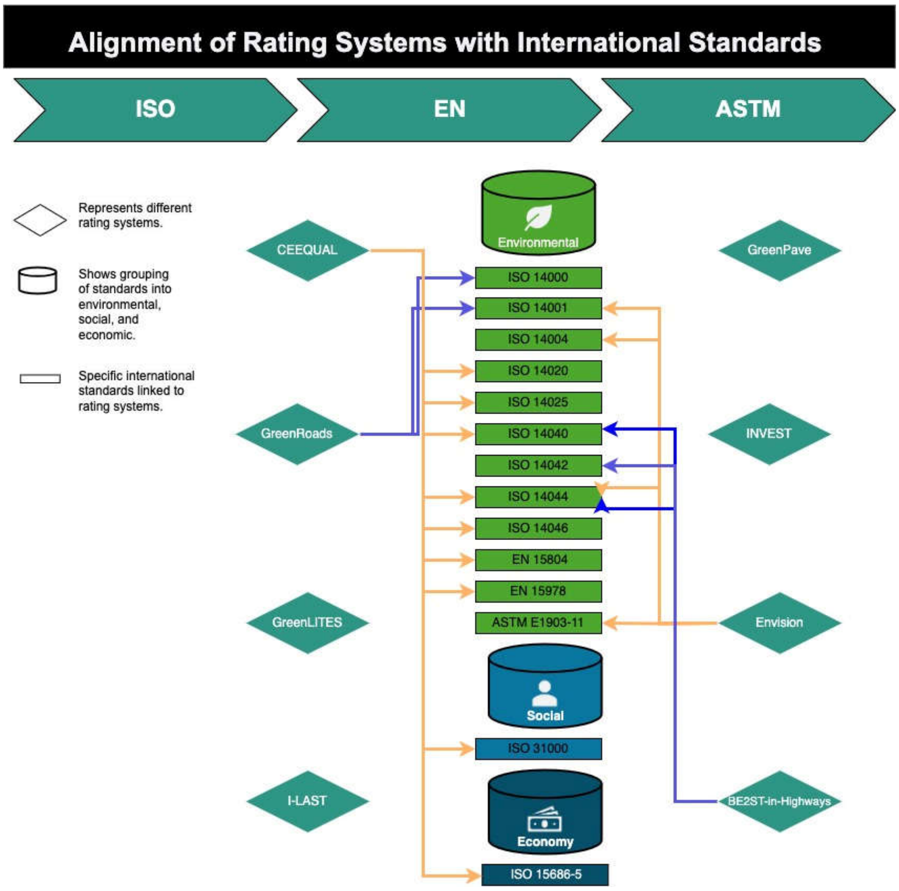

Figure 4. Alignment of rating systems with international standards [29–32,37–39,51,55–58].

When focusing on ASTM standards, emphasis is given to ASTM E903 [59], which outlines procedures for testing solar absorptance, reflectance, and transmittance of materials used in construction, aiding in the selection of energy-efficient and environmentally friendly building materials. Additionally, ASTM E1903-11 [60] provides guidelines for evaluating and mitigating environmental impacts associated with building systems and operations, facilitating the implementation of sustainable practices throughout the life cycle of construction projects. Similarly, ASTM E1980-11 [61] offers methodologies for calculating the Solar Reflectance Index (SRI). Collectively, these ASTM standards contribute to promoting environmental sustainability practices and driving positive environmental outcomes in the construction sector. GreenRoads specifically incorporates ASTM E903 within its sustainability rating system. Additionally, ASTM E1903-11 and ASTM E1980-11 are included in the Envision sustainability rating system.

Beyond ISO, EN, and ASTM standards, additional references and organizations play a crucial role in guiding environmental sustainability in the road and construction sector. Among them, Building Research Establishment (BRE) standards ensure adherence to rigorous environmental and sustainability criteria in construction projects, fostering the use of eco-friendly building materials and practices [16]. The standards issued by the National Institute for Occupational Safety and Health (NIOSH) prioritize worker safety while contributing to sustainable construction practices [38]. Adherence to Environmental Protection Agency (EPA) Tier 4 standards ensures the use of cleaner and more fuel-efficient construction equipment, reducing emissions and environmental impact [62]. The National Pollutant Discharge Elimination System (NPDES) requirements and Stormwater Pollution Prevention Plans (SWPPP) standards safeguard water quality by mitigating stormwater runoff pollution from construction sites [63]. Standards set by the American Association of

State Highway and Transportation Officials (AASHTO) and the United States Department of Transportation (USDOT) provide guidelines and specifications for sustainable transportation infrastructure development [38]. Similarly, the Canadian Council of Ministers of the Environment (CCME) standards offer guidance on environmental protection and sustainable development practices in construction projects across Canada [27]. Collectively, these methodologies and standards contribute to fostering environmental sustainability and driving positive environmental outcomes in the construction sector. Within various sustainability rating systems (SRSs), different references are utilized to promote environmental sustainability in construction projects. By way of example, CEEQUAL follows the Building Research Establishment (BRE) standards, GreenRoads emphasizes the use of pavers meeting the National Institute for Occupational Safety and Health (NIOSH) standard and Environmental Protection Agency (EPA) Tier 4 standards to enhance sustainability, GreenLITES incorporates requirements related to the National Pollutant Discharge Elimination System (NPDES), and I-LAST prioritizes compliance with Stormwater Pollution Prevention Plans (SWPPP) standards and NPDES requirements to safeguard water quality. Standards set by the Utah Department of Transportation (UDOT) are utilized in INVEST, while the Envision system is in compliance with standards issued by the United States Department of Transportation (USDOT) and the Canadian Council of Ministers of the Environment (CCME) [64].

3.5.3. Social Sustainability Standards

When focusing on social sustainability, a robust framework of standards is crucial for guiding organizations towards responsible practices and measurable outcomes that prioritize the well-being of communities, employees, and stakeholders. Several ISO standards are dedicated to addressing social aspects of sustainability, offering guidelines and methodologies to promote social responsibility, equity, and inclusivity. ISO 26000 [26] serves as a cornerstone in this effort, providing guidance on social responsibility for organizations. This standard outlines principles and practices that organizations can adopt to operate ethically and contribute positively to societal development. By addressing social issues such as human rights, labor practices, fair operating practices, community involvement, and consumer protection, ISO 26000 helps organizations enhance their social impact and contribute to sustainable development goals [35,65]. Additionally, ISO 37104 [66] focuses on a management system for sustainable development, offering principles and practices for assessing, implementing, and monitoring sustainable development initiatives at the community level. By promoting community engagement, social equity, and inclusivity, ISO 37104 supports the creation of thriving and resilient communities that prioritize the well-being of all residents [35]. Moreover, ISO 30400 [67] provides guidelines for human resource management, offering organizations a framework for effectively managing their workforce. By addressing aspects such as recruitment, training, performance management, diversity, and inclusion, ISO 30400 helps organizations create inclusive workplaces that foster employee well-being, satisfaction, and professional development [6,11]. Additionally, ISO 21931-1 [42] provides guidance on assessing the sustainability of construction works, focusing on environmental, economic, and social aspects throughout the life cycle of construction projects. By evaluating sustainability performance, organizations can optimize resource utilization, minimize potential social risks, and contribute to broader sustainability goals in the construction sector [62,68]. Integrating these ISO standards into organizational practices and processes can help organizations enhance their social sustainability performance, promote ethical and inclusive business practices, and contribute to the well-being of communities and society.

Among European standards, EN 15643 [47] and EN 16309 [69] stand out as fundamental tools for evaluating the social dimensions of building sustainability. EN 15643 offers a structured approach to assess the social impact and performance of buildings. This standard provides a comprehensive framework that encompasses a wide range of social factors, including accessibility, safety, health, comfort, and overall well-being of occupants. By establishing guidelines and methodologies for evaluating these social aspects, it facilitates the creation of buildings that not only meet environmental and economic criteria but also contribute positively to the social aspect of communities [6,35]. In parallel, EN 16309 introduces a calculation methodology specifically tailored for assessing the social performance of buildings. This standard offers a systematic approach for quantifying and evaluating social aspects such as accessibility, inclusivity, community engagement, and social cohesion within the context of building sustainability. By providing a standardized methodology for assessing social performance, EN 16309 enables stakeholders to measure and compare the social impact of different buildings, thereby guiding decision-making processes towards more socially sustainable outcomes [39,65]. In the field of sustainable construction, the significance of EN 15643 and EN 16309 in fostering a holistic understanding of building sustainability is also recognized. By incorporating social dimensions into the assessment frameworks, these standards contribute to the development of buildings that not only minimize environmental impact but also prioritize the well-being and quality of life of occupants and communities. Thus, further research and application of these standards are essential for advancing the agenda of socially sustainable construction practices and promoting the creation of built environments that foster inclusivity, equity, and social cohesion [11,62].

Surprisingly, none of the ISO and EN standards dedicated to social sustainability are referenced or integrated within the studied sustainability rating systems, despite their significance in guiding organizations towards responsible social practices and enhancing the social performance of buildings [11,65]. This represents a notable gap in formally recognizing and incentivizing organizations and buildings that prioritize social responsibility, equity, and inclusivity [35,39]. Moreover, such a lack can limit the effectiveness of sustainability rating systems in driving meaningful social changes within the built environment and promoting socially responsible practices among stakeholders [12,62]. As a result, there is a pressing need for the inclusion of these standards within sustainability rating systems to ensure a comprehensive and integrated approach to sustainability assessment that encompasses environmental, economic, and social dimensions [3,11]. As illustrated in Figure 4, only the CEEQUAL rating system references ISO 31000 [57], which, while not directly focused on social sustainability, provides guidelines for risk management [5,70].

3.5.4. Economic Sustainability Standards

ISO 15686-5 [58] provides guidelines for conducting life cycle costing, which involves assessing the total costs associated with the entire life span of a building or constructed asset [30,65]. This standard assists stakeholders in making informed decisions by considering all costs, including initial investment, operation, maintenance, and disposal, over the asset's life cycle [5,11]. By incorporating life cycle costing principles, organizations can optimize resource allocation, minimize life cycle costs, and enhance the sustainability and efficiency of their assets [4,71]. As shown in Figure 4, ISO 15686-5 is utilized in the CEEQUAL rating system, where it contributes to the assessment of buildings and constructed assets' life cycle costs and supports the system's goal of promoting sustainability within infrastructure projects by considering economic factors alongside environmental and social aspects.

Additionally, the ISO 59000 series represents a significant advancement in standardization efforts aimed at promoting the circular economy [37]. Developed by the ISO/TC323 technical committee, these standards aim to provide comprehensive guidance and frameworks for organizations across various sectors to adopt the principles of a circular economy. The series encompasses standards such as ISO 59004 [72], which defines fundamental terminology and core principles; ISO 59010 [73], offering transition guidance for businesses; and ISO 59020 [74], providing methodologies for measuring and assessing circularity performance. The overarching goal of the ISO 59000 series is to facilitate the transition towards a more sustainable global economy by encouraging more efficient resource utilization and promoting circular resource flows, contributing to environmental and economic sustainability on a global scale. Despite the importance of the ISO 59000 series in promoting the principles of a circular economy, it is notable that these standards are not currently referenced or integrated within any sustainability rating system [27].

4. Conclusions

Road sustainability rating systems (SRSs) have gained increasing prominence as tools for supporting responsible decision-making in road projects worldwide [12,27]. Despite their growing adoption, they have yet to be fully embraced as trusted advisers in infrastructure development [7,27]. Nonetheless, the practices recommended by these systems have the potential to significantly enhance the sustainability of road pavement infrastructure [4,5].

This paper offered a comprehensive review of the main sustainable road rating systems, aiming at comparing their functionalities and evaluating their alignment with the requirements of flexible pavement infrastructure [7,75]. This review encompasses a detailed analysis of the general characteristics, structural frameworks, criteria weighting, compliance with the three pillars of sustainability, and adherence to international benchmarks and standards [7,35]. Eight notable rating systems were analyzed: CEEQUAL, Greenroads, GreenLITES, GreenPave, I-LAST, INVEST, BE2ST-in-Highways, and Envision [5,14,19]. The findings revealed critical dimensions of sustainability, providing valuable insights into the relative weightings of environmental, social, and economic considerations [11,27]. The analysis identified a clear hierarchy: environmental well-being emerged as the most significant dimension, contributing 43% to the overall sustainability rating. Social well-being followed closely at 42%, while economic well-being, at 15%, represented the lowest weight. These results establish a foundation for understanding the diverse priorities embedded in sustainable road pavement practices.

Looking ahead, this study underscores the necessity of continued research to evaluate the effectiveness of various categories and indicators. Such efforts should investigate whether a more extensive set of indicators could achieve comparable overall results, thereby advancing the comprehension and application of sustainability in road infrastructure. Given the historical challenges in quantifying and implementing social and economic indicators, this paper advocates for leveraging the life cycle assessment methodology aligned with ISO standards 14040 and 14044. This approach promises to address previous limitations and foster the development of innovative, holistic sustainability metrics. In conclusion, this paper consolidates existing knowledge while charting pathways for future research. By elucidating weight contributions, identifying areas for further exploration, and recommending methodological improvements, it contributes to the refinement of sustainability rating systems in highway construction. These insights aim to inform future initiatives, ensuring that efforts to develop sustainable road pavement infrastructure align with the multifaceted dimensions of well-being and resilience in an evolving global landscape.

Future Research Direction

This study identifies several key areas for future research to further advance sustainability rating systems (SRSs) for road infrastructure. First, there is a pressing need to critically assess the effectiveness of existing indicators and explore whether their expansion or refinement could yield more accurate and comprehensive sustainability outcomes. While environmental considerations have been widely prioritized, significant gaps remain in addressing the social and economic dimensions of sustainability. Future work should focus on developing robust metrics to capture social aspects such as worker health and safety and community well-being. In parallel, economic indicators must evolve to incorporate life cycle costs, long-term economic benefits, and financial resilience, enabling a more holistic evaluation of road infrastructure projects.

To bridge these gaps, integrating the life cycle assessment methodology, in line with ISO standards 14040 and 14044, offers considerable potential for advancing sustainability assessments, particularly in the environmental and social domains. While environmental life cycle assessment is well-established for evaluating environmental impacts, the adoption of social life cycle assessment can provide valuable insights into social impacts across the project life cycle, including material sourcing, construction, use, and maintenance phases. By combining these methodologies, future research can identify critical hotspots, quantify trade-offs between environmental and social priorities, and provide a science-based foundation for more balanced and integrated sustainability evaluations. Such efforts will contribute to enhancing the credibility, comprehensiveness, and applicability of SRSs, ensuring they better align with the evolving global imperatives of sustainable development.

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