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*Systematic Review*

# Towards Sustainable Roads: A Systematic Review of Triple-Bottom-Line-Based Assessment Methods

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**Abstract:** This review summarizes the methods and approaches for quantifying the sustainability performance of roads based on the Triple Bottom Line (TBL) concept. Furthermore, research gaps and challenges in the sustainability assessment of roads are identified. While prior studies explored the environmental and economic dimensions, no comprehensive overview of holistic sustainability assessment of roads exists. A systematic literature review (SLR) was conducted to identify relevant studies. Two assessment approaches were identified: (1) life-cycle-based approaches and (2) sustainability rating systems (SRS). Most of the reviewed studies applied life-cycle-based methods, such as Life Cycle Sustainability Assessment or a combination of Life Cycle Assessment, Life Cycle Costing, and selected social indicators. Heterogeneity in functional units was observed, with most studies opting for a dimension-based instead of a function-based reference. There was high variability regarding the life cycle stages, indicators, and impact assessment methods. Concerning the interpretation methods, most studies calculated a sustainability index or applied Multi-Criteria Decision-Making methods. The SRS presented a similar structure with different levels of aggregation. Furthermore, aspects such as planning, leadership, innovation, and construction activities were addressed. The results of this SLR contribute to expanding the knowledge regarding road sustainability and provide insight into common frameworks, guidelines, and best practices for the sustainability assessment of roads and pavements.

**Keywords:** sustainability assessment; life cycle sustainability assessment (LCSA); sustainability rating systems; triple bottom line; roads; pavements

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## 1. Introduction

Road infrastructure is connected to the economic and social development of countries [1]. In fact, roads are critical in enabling the movement of people and goods [2]. Road transport is the most common mode of passenger transport and the second most common mode of freight transport in the European Union [3,4]. Furthermore, roads link cities, towns, rural areas, and regions, promoting social and economic interactions, trade, and commerce [5]. Indeed, the importance of roads for the proper functioning of society and economy is evident.

Current trends show that road networks are expanding, especially in developing countries [6]. Furthermore, existing roads require regular maintenance and repair to continue fulfilling their function [7]. In this context, there is ample evidence that road infrastructure significantly impacts their surroundings, positively and negatively [8]. On the one hand, the positive effects of roads on the economy and society are many. Road infrastructure allows improved accessibility to markets and supports overcoming economic isolation, leading to the growth of towns, cities, and regions [9,10]. In addition, the construction of roads is connected to economic growth and national wealth [11–13]. Roads also provide job opportunities and access to economic activities and raw materials [10,14]. Moreover, they can contribute to savings in travel time, which is, in turn, connected to an increase in productivity [9,14]. In developing countries, roads support social mobility, migration, and, thus, greater economic opportunities [12]. On the other hand, roads are responsible for major environmental impacts [15,16]. Not only do roads generate harmful emissions throughout their life cycle, but they also lead to increased resource and energy consumption [17]. Moreover, roads are responsible for several social problems, including worker exposure to pollutants and work-related injuries and illnesses, construction and traffic noise, and others [9]. Because of their crucial function and their significant impacts, roads should not only meet technical requirements but also ensure that their sustainability performance aligns with and contributes to overarching sustainability goals, such as the United Nations Sustainability Development Goals (SDGs). Therefore, the sustainability performance of roads should be accurately measured. Several studies have already addressed the environmental impacts of roads and pavements. A commonly used method for this purpose is Life Cycle Assessment (LCA) [18,19]. LCA is a robust and standardized method for assessing the environmental impacts of products and services throughout their life cycle and is widely used both in industry and academia [20]. However, it focuses only on the environmental impacts. In turn, other studies focusing on economic and social dimensions have also been published on several occasions. For example, many studies use Life Cycle Costing (LCC) to assess economic impacts throughout the product life cycle [21], while Social Life Cycle Assessment (S-LCA) is applied to evaluate social impacts with a life cycle perspective [22]. It should be noted, however, that the latter is less widely applied than its environmental and economic counterparts. Nevertheless, even these studies do not provide a holistic picture of the sustainability performance of roads.

As mentioned before, many studies on roads and pavements already address one sustainability dimension, usually the environmental one. In addition, several literature reviews summarize the findings of these assessments [23–31]. However, due to their environmental and social impacts as well as their economic significance, road infrastructure projects should be evaluated using a Triple Bottom Line (TBL) approach. The TBL is a paradigm for assessing the performance of products and organizations based on the environmental, economic, and social dimensions [32]. This approach forms the basis of the Life Cycle Sustainability Assessment (LCSA) concept proposed by Kloepffer [33] and Finkbeiner et al. [34]. Although not as widespread as stand-alone LCA or LCC, LCSA is used in many sectors, such as building, energy, transport, and manufacturing [35]. There are other approaches to holistic sustainability assessment. In the building sector, sustainability rating systems (SRS) have been used since the late 1990s to award more sustainable buildings and promote sustainable practices [36]. In recent years, there has been a trend of using a similar approach for road infrastructure [37].

Against this background, the question arises: Have TBL-based assessments been used to evaluate the sustainability performance of roads? To answer this question, a systematic literature review (SLR) was conducted to identify studies that have applied holistic sustainability assessment in the context of roads and pavements. The authors aim to provide an overview of the methods used and how they are applied. In particular, this SLR examines which standards and approaches are used as a reference and which goals and system boundaries are defined. Due to the current research interest in LCSA and the widespread use of LCA and LCC on roads and pavements [38], the authors hypothesize that several studies on LCSA will be found. Therefore, several aspects related to the application of this methodology are addressed. The investigated research questions are as follows:

1. Have TBL-based assessments been used to evaluate the sustainability performance of roads?
2. What approaches are followed for assessing the sustainability impacts of roads considering the three dimensions of sustainability?
3. How were the life-cycle-based methods applied? And more specifically,
    (a) Was the framework proposed by Kloepffer [33] and Finkbeiner et al. [34] followed?
    (b) What standards and guidelines are used as a reference?

(c) What are the goals and system boundaries of the studies?
(d) What functional units (FUs) are used?
(e) What life cycle stages do the studies address?
(f) What types of data were used in the assessments regarding sources and quality?
(g) What indicators were used?
(h) How are the results interpreted (combined or separately)?
(i) What methods were used for the visualization of results?

4. If other approaches were used for the sustainability assessment, how were they applied?
5. What are the main challenges identified?

This SLR provides a better understanding of the approaches, methods, and challenges associated with the holistic sustainability assessment of roads and pavements, including the application of life-cycle-based methods. In particular, we identify common frameworks, standards, guidelines, best practices, and remaining challenges in the sustainability assessment of roads and pavements. The results can represent an important reference for researchers, practitioners, and policymakers for driving practices and providing guidance for conducting robust assessments. Such a central reference is particularly crucial to foster and advance harmonized approaches for the sustainability assessment of roads.

In the following, a short introduction to the sustainability methods addressed by this SLR (i.e., LCSA and SRS) is offered in Sections 1.1 and 1.2). This is followed by an overview of previous work on LCSA in the building and road sectors, highlighting present research gaps that are addressed by this paper. In Section 3, the methods to conduct the SLR were described. The results are then presented in Sections 4 and 5, respectively, while the concluding remarks are presented in Section 6.

### *1.1. Life Cycle Sustainability Assessment*

Life Cycle Sustainability Assessment (LCSA) evaluates the environmental, economic, and social performance of products or services along their life cycle [39]. The concept of LCSA was introduced by Kloepffer [33], who expressed the framework in the form LCSA = LCA + LCC + S-LCA. In this context, LCA covers the environmental dimension [19,40], LCC covers the economic dimension [41], and S-LCA covers the social dimension [42]. The above formula does not imply a mathematical addition of results. In fact, the results of the individual assessments are based on different models and involve indicators measured in multiple units, hindering a simple sum. In contrast, Kloepffer's formula connotates a combination of the three methods, meaning that the methods are applied to the same product or service considering the same functional unit (FU) within equivalent system boundaries [39,43,44]. System boundaries are defined as the union of all process units relevant to at least one of the three dimensions of sustainability [43]. The FU is defined by UNEP [39] as the reference unit in LCA studies that quantifies the performance of the product system. To achieve this, the FU should be clearly definable in its unit, size, duration, and quality level [45].

Within LCSA, LCA is the most widely used and standardized method [19,40,46]. The main objective of LCA is to identify and compare the potential environmental impacts across all life cycle stages [46]. The life cycle approach helps prevent burden shifting from one life cycle stage to another or between different environmental impacts [47]. LCA allows for compiling all relevant inputs and outputs of a product system and evaluates their potential environmental impacts [19]. LCA has four phases: (1) goal and scope definition, (2) life cycle inventory (LCI), (3) life cycle impact assessment (LCIA), and (4) interpretation. The first phase encompasses the reasons for conducting the study and its application [19]. It also describes the studied product system, defines the FU, system boundaries, and other relevant methodological choices, such as selecting the impact assessment methods and impact categories [48]. Next, in the LCI, data on all relevant flows are gathered in line with the goal and scope [49]. The LCIA follows, in which the emissions and flows collected in the previous phase are assigned to different impact categories (classification), and their environmental impact is calculated through multiplication with a characterization factor (characterization) [19]. Finally, in the interpretation phase, the outcomes of the LCIA are evaluated in light of the goal and scope [19]. As mentioned above, LCA is a standardized method according to ISO 14040 and ISO 14044 [19,40]. Other norms regulate the application of LCA in different areas of the construction sector, such as ISO 21930 and EN 15804 for construction products, EN 15978 for buildings, and prEN 17392-1 for asphalt mixtures (withdrawn) [50–53].

LCC is a method for evaluating all relevant costs of a product throughout its entire life cycle and is often used to compare alternatives of products and services [41,54]. LCC captures all actual costs and revenues associated with a type of asset [55]. Therefore, it integrates a long-term perspective in the decision-making process, as the consideration goes beyond the purchase price or acquisition costs [56]. Full costs can include design and development costs; production and implementation costs; operating costs; end-of-life (EoL) costs; acquisition and financing costs; and installation, commissioning, and training costs [56]. There are three main types of LCC: conventional (cLCC), environmental (eLCC), and societal (sLCC) [57]. While cLCC focuses on the perspective of a single stakeholder with the consideration of internal costs only, eLCC considers all relevant stakeholders and, in addition to the internal costs, may include expected environmental costs that can be internalized in the future [58]. Finally, sLCC extends the scope of eLCC to include the costs for social externalities [57]. Although LCC is the oldest of life-cycle-based methods, it is not as standardized as LCA. In the construction sector, the ISO 15686-5 (LCC of buildings) is used as a reference in several studies [59].

S-LCA assesses the positive and negative social impacts of products from a life cycle perspective [42,60]. This is the newest method used in LCSA [61]. There are no standards for S-LCA yet, although one is being drafted [62]. Furthermore, the United Nations Environment Program (UNEP) developed documents to guide the application of the method, the Guidelines for S-LCA and the Methodological Sheets [42,63]. By considering the life cycle and using a systematic process for capturing and reporting social impacts and benefits, S-LCA distinguishes itself from other social impact assessment methods, such as fair trade or corporate social responsibility (CSR) [60]. S-LCA builds on the LCA framework (four phases), with the main difference being that the outcomes of a social assessment are closely linked to the considered stakeholder. The Guidelines for S-LCA define the following stakeholder categories: Workers, Local Community, Society, Consumers, Value Chain Actors, and Children [42]. Moreover, the guidelines identify two types of social impact assessments: (1) Reference Scale, focused on the evaluation of social performance or risks, and (2) Impact Pathway, focused on the quantification of social impacts through the evaluation of cause–effect chains with classification and characterization steps [42].

### *1.2. Sustainability Rating Systems*

Especially in the building sector, another approach for measuring sustainability performance is used—sustainability rating systems (SRS), also known as Green Building Rating Systems (GBRS) or Sustainability Certification Schemes [64]. SRS are voluntary frameworks that promote adopting more sustainable practices in projects throughout the design, construction, and operation [65]. Furthermore, the proposed practices typically go beyond mandatory regulatory requirements [66]. SRS assess the sustainability performance of buildings by measuring their compliance with selected sustainability criteria [67,68]. A criterion is a requirement for the project defined before the start of the assessment process [69]. Each criterion is assigned a weight, which establishes how much influence it has on the final score. SRS have a rating scale that is independent of the criterion weight and defines the minimum requirements for compliance [70].

SRS are already widely developed and used in the context of buildings. Nearly 600 SRS exist worldwide [71]. Some of the most disseminated SRS are Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM), and Comprehensive Assessment System for Built Environment Efficiency (CASBEE) [72]. In the field of infrastructure and roads, however, there is still a notable lack of SRS [73]. Some examples of SRS exist in the market, such as Greenroads and BREEAM Infrastructure [74,75]. However, these are not as widely established as their equivalent for buildings.

## 2. Previous Works and Research Gaps

Research on LCSA is growing [38]. Backes and Traverso [76] reviewed the application of LCSA in the construction sector and evidenced this fact. Although a growing trend in LCSA studies was identified, the review showed that this method is currently rarely used in practice [76]. Moreover, this study highlighted a current gap in the field: while many publications claim to be LCSA, only a few conducted studies encompassing the three dimensions. Furthermore, a screening of the existing literature showed several contributions to the application of LCSA in buildings. For example, Amini Toosi et al. [77] reviewed the use of LCSA in building energy retrofitting. Although challenges related to large data demand, uncertainty, and complexity were encountered, the authors also demonstrated an increase in studies combining indicators for LCA, LCC, and S-LCA. The lack of consensus on how to link the three dimensions was also underlined. In particular, the combination of different metrics and the maturity of the methods was listed as a challenge to overcome [77]. Bhyan et al. [78] conducted a similar review focused on residential buildings. No studies were found assessing all three dimensions; most of them neglected the social and economic dimensions.

Some studies attempted to identify the most relevant indicators for building LCSA. Janjua et al. [79] identified relevant impact categories, key performance indicators, thresholds, and weightings for LCSA of buildings from a literature review and consensus surveys. A similar review was conducted by Lu et al. [80], who identified indicators for the economic, environmental, and social dimensions. The findings were used to propose an LCSA framework for buildings, while the connection to Building Information Modelling (BIM), artificial intelligence, and the Internet of Things is proposed to advance the LCSA methodology. Also related to BIM, Zulkefli et al. [81] highlighted the extensive work that has been done to link LCA and LCC to BIM. However, very few efforts have been made so far to link LCSA to BIM tools.

Despite these works focusing on the building sector, no reviews were found that examined the use of LCSA in the specific context of roads and pavements. Acai and Amadi-Echendu [65] reviewed different SRS for pavement infrastructure used in the praxis, but LCSA was not addressed. Suprayoga et al. [82] developed a set of indicators for the sustainability performance of road infrastructure. Their indicators cover the topics of biodiversity, mobility, pollution, climate change, resource efficiency, integrative planning, and decision-making. Focused on bridges, Navarro et al. [83] identified Multi-Criteria Decision-Making (MCDM) methods for sustainable design. The Simple Additive Weighting (SAW) and Analytic Hierarchy Process (AHP) methods were identified as the most used MCDM approaches in the context of bridges, although Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and Preference Ranking Organization METHod for Enrichment Evaluation (PROMETHEE) appeared to have gained more relevance [83]. De Bortoli et al. [84] developed a sustainability assessment method integrating environmental, economic, and social indicators addressing pavement resurfacing and pavement-vehicle interaction. This study reviewed sustainability assessment methods for the environmental and economic dimensions and a combination of the two [84]. Furthermore, the developed assessment method was applied in a case study to illustrate its practicality [85].

Previous work on the sustainability assessment of roads and pavements has concentrated on LCA. Several studies have addressed methodological aspects of LCA applied to roads and pavements. Hoxha et al. [24] identified key aspects missing in LCA studies of urban roads, such as the lack of reproducibility of the studies and the heterogeneity in the FUs. Hoxha et al. [23] analyzed the challenges preventing the comparison of outcomes, such as a lack of consensus in FU and indicators and a lack of transparency in the disclosure of study parameters. Furthermore, Lendra et al. [25] found that most road LCA studies focused only on selected life cycle stages, while only a few studies assessed the whole life cycle of roads. Aryan et al. [86] made a critical review of LCA studies of road pavements and infrastructure, focusing on the chosen goals, impact categories, life cycle stages, approaches, and limitations. The results highlighted several aspects that need to be addressed in future studies, such as including all supporting infrastructures of roads in the environmental assessment, conducting sensitivity and uncertainty analyses, and addressing biodiversity-related impacts [86].

The application of LCA in decision-making processes was also examined. Rangelov et al. [26] identified LCA approaches influencing decisions during the project planning and delivery process, focusing on pavements. Challenges such as the lack of communication, transparency, and consistency in the calculation of the environmental impacts, as well as the lack of benchmarks, were cited. Consulted stakeholders in this study recommended the adaptation of LCA to the conditions of different project stages—e.g., simplified tools to aid the planning process [26].

Reviews on LCA also addressed the environmental performance of selected materials, structures, and measures throughout the life cycle of pavements. For instance, Castro et al. [27] summarized the $CO_2$ emissions of different LCA studies. However, the comparison was focused only on the FU—aspects such as system boundaries, type of road, type of material, etc., were not considered. Liu et al. [29] identified hotspots in the $CO_2$ emissions of the different life cycle stages of roads from the literature. The hotspots included vehicle emissions, material production, as well as construction and maintenance activities. Balaguera et al. [30] focused on LCA for assessing recycled materials as alternative road materials. The biggest challenge was identified as the lack of holistic assessments that include economic and social impacts, which are seen as relevant. Inyim et al. [31] aimed to point out through a review which pavement type is the most sustainable from the environmental perspective by examining the available literature. Due to the lack of harmonization of the studies regarding assessed life cycle stages, FUs, impact categories, and methods to assess uncertainty, the authors conclude that it is not possible to identify the most sustainable pavement option [31]. This conclusion is consistent with the findings of Hoxha et al. [23]. Finally, Liu et al. [28] evaluated the effectiveness of maintenance activities for pavements and how the environmental impacts of pavement activities are assessed. Among other aspects, the authors found that the categories of energy consumption and Global Warming Potential (GWP) were the most assessed among the studies.

Regarding the economic dimension, only one review focused on LCC applied on roads. In particular, Goh and Yang [87] performed a literature review, surveys, and interviews on the current application of LCC in highway projects. In the study, the main challenges connected to LCC are the limited capacity of existing LCC models, poor data quality, and difficulties in examining long-term community environmental issues.

Finally, it was examined if any studies addressed the combination of different sustainability dimensions without a TBL approach, i.e., combining the environmental and economic, the environmental and social, or the economic and social dimensions. The screening showed that, so far, all studies in this direction only addressed the combination of LCA and LCC. Hasan et al. [88] highlighted critical aspects and identified hotspots connected to the assessment of these two dimensions. For LCC, the authors addressed the adopted cost parameters, uncertainty-related issues, time- and traffic-related parameters, and design parameters of the studies. For LCA, aspects such as FU, system boundaries, analyzed scenarios, and consulted databases were examined. Most of the reviewed studies conducted either LCA or LCC, with very few exceptions of combined approaches. Alaloul et al. [89] also reviewed studies addressing the integration of LCA and LCC of roads. The authors propose an integrated LCA-LCC framework focusing on $CO_2$ carbon costs.

Similar studies were conducted to assess specific road material groups. For instance, Picado-Santos et al. [90] examined the environmental impacts and life cycle costs reported in previous studies on the use of crumb rubber on roads, while Salehi et al. [91] investigated the implementation of LCA and LCC to assess the performance of recycled materials. Finally, Gaudenzi et al. [92] aimed to provide an overview of the use of lignin on roads.

Although the focus was on the technical properties of lignin, the authors also discussed the application of LCA and LCC to assess the impacts of this material [92]. In general, although LCA and LCC were examined in the mentioned studies, no integrated approach for the interpretation of the outcomes was addressed.

## 3. Methods

The present study comprises an SLR, a method for understanding the current state of the existing body of work and identifying research gaps and priorities [93,94]. For a transparent, comprehensive, and accurate review, the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) statement was followed [94,95]. The PRISMA statement has guidelines for the definition of eligibility criteria, information sources, and search strategy, as well as for the data collection process and the report of the collection outcomes. Since this method was originally developed for application in the health sector, several aspects were adapted to the field of sustainability assessment. For instance, risk of bias assessments and sensitivity analyses, among other suggested assessments, are suggested in the PRISMA statement but were not carried out in this review. Furthermore, the PRISMA method was complemented with a backward snowballing approach. Backward snowballing consists of using the bibliography of previously identified papers (using the PRISMA statement) to find additional relevant publications to extend the literature review [96]. This approach allowed the identification of relevant studies that were not indexed in the consulted databases.

This study is structured in five phases, as shown in Figure 1. Phase 1 focuses on the definition of the main goals of the study and the research questions, all of which were presented in Section 1. In the next step (Phase 2), the methods for the SRL were chosen (PRISMA statement and backward snowballing, as described above).

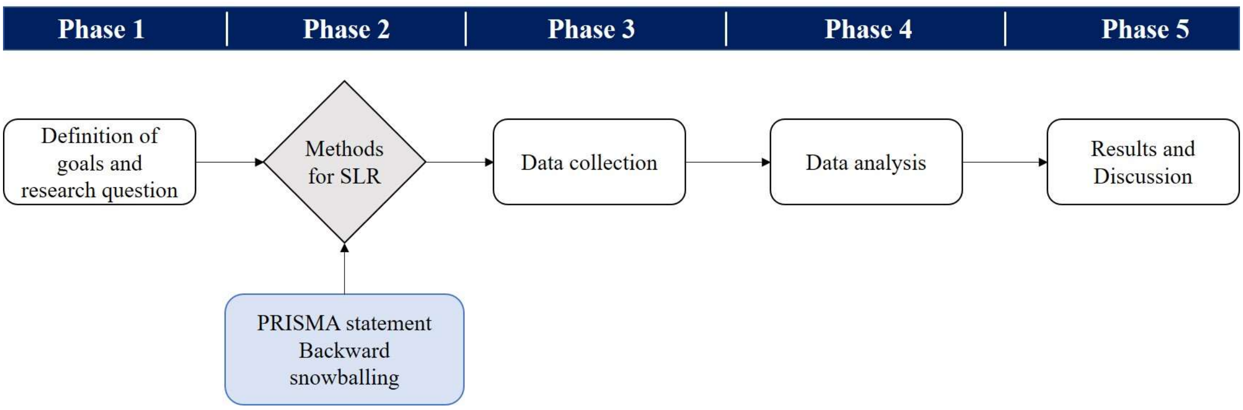


**Figure 1.** Research methodology.

For the SLR, Scopus and Web of Science (WoS) were the chosen databases due to their multi-disciplinary coverage and the inclusion of high-quality, peer-reviewed literature [97,98]. The consultation of the databases occurred on 20 February 2023. The focus of this study is on the holistic sustainability assessment of roads and pavements (i.e., TBL approach). Therefore, the following search string was used:

TITLE-ABS-KEY ((“sustainable” OR “sustainability assessment” OR “life cycle sustainability assessment” OR “LCSA”) AND (“road” OR “pavement” OR “highway” OR “motorway”)).

The collected studies were then screened in three stages (Figure 2). The first screening consisted of the review of titles and abstracts found in the databases mentioned above. Studies focusing on roads combined with sustainability assessment with a life cycle perspective and the TBL approach and/or using MCDM methods to assess sustainability performance were selected. The list of the selected studies in both databases was consolidated and validated for duplicates in preparation for the second screening. The second screening consisted of checking which articles were retrievable in full text. In the third screening, the full texts were revised, and the most relevant ones were selected. In this screening, contributions were discarded due to one of four reasons: (1) not all three sustainability dimensions were considered; (2) the study is not about roads, road pavements, or road infrastructure at project level (studies from a network perspective were neglected); (3) the paper is purely a review, i.e., no framework nor case study was developed or carried out; or (4) the paper is not about sustainability assessment, but focuses mainly on the analysis of potentially sustainable technologies or materials. The chosen papers were reviewed, and data were extracted and synthesized. Furthermore, their cited papers were reviewed to assess if any other relevant contribution had not been listed in the consulted databases (snowballing).

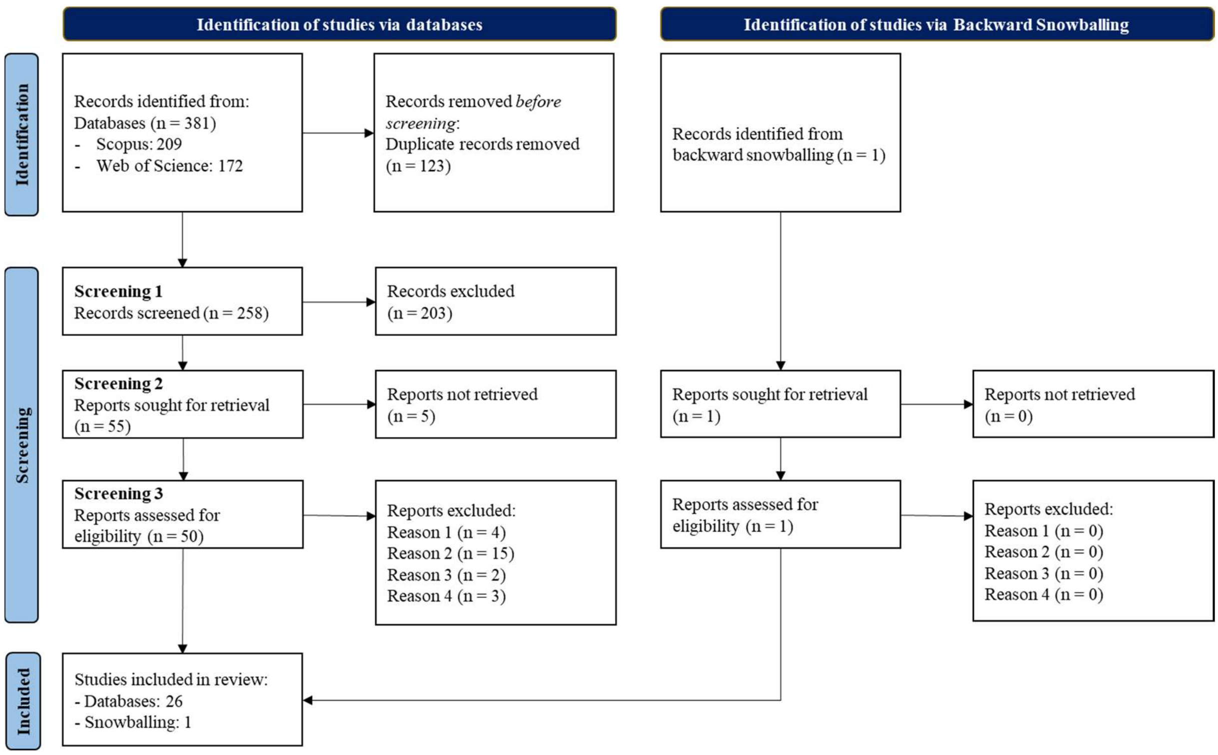


**Figure 2.** Identification, screening, and selection of studies following the PRISMA statement.

The data were collected from the identified studies (Phase 3) and organized in a table using Microsoft Excel. For all papers, the authors, year, title, publication journal, document type, keywords, and study type were documented. Furthermore, the assessment method(s), object of study, geographical context, and goal were reported.

Due to the nature of the sustainability assessments in the selected studies, two different groups are distinguished: (1) life-cycle-based methods and (2) SRS. The studies in Group 1 develop and apply methods such as LCSA (as defined by Kloepffer [33] and Finkbeiner et al. [34]) or any other comparable approaches, such as a combination of LCA (environmental impacts), LCC, or Cost–Benefit Analysis (CBA) (economic impacts) and certain social indicators (social impacts) or Economic Input–Output based on the TBL approach. Group 2 comprises studies that define a set of criteria, weighted or with a score, aiming to measure the performance of projects. The criteria can either be in the form of measurable indicators or implementable 'best practices'. In this regard, data that characterize the studies in the two identified groups were collected, as shown in Section 4.

Following this grouping approach, the collected data were analyzed (Phase 4). For all studies, publication trends were identified based on the years of publication and the country of affiliation of the first author (Section 4.1). Furthermore, the results of the keyword analysis are provided. For this, the records of the final selected studies were imported into VOSViewer [99]. With this tool, an analysis of co-occurrence based on keywords was performed. For this, the full counting method was chosen, where each co-occurrence link has the same weight. A minimum number of keyword occurrences was defined (2), for which 40 words (out of 198) met the threshold. From the 40 keywords, 1 term was excluded due to being considered redundant (i.e., 'road infrastructure' since 'road' was already present). Finally, 39 items were analyzed.

## 4. Results

A total of 27 publications were selected to conduct the systematic review and are depicted in Table 1. Most of the studies consisted of the development of a framework for the sustainability of roads and pavements with its application in a case study. On a few exceptions, no practical demonstration of the framework was carried out. This section is structured as follows. First, publication trends within the selected publications are addressed in Section 4.1. Furthermore, the results of the keyword analysis are provided. Subsequently, the content-related results of the review are presented in Section 4.2. Finally, the analysis of the content of the studies in Group 1 (Section 4.2.1) and Group 2 (Section 4.2.2) is provided.

### *4.1. Publication Trends*

The analysis of the publication years of the studies shows that the earliest study regarding sustainability assessment of roads and pavements appeared in 2010 (Figure 3). Although this first study belongs to Group 2 (SRS), this is consistent with the first publication on LCSA in 2008 [33] and the publication of the LCSA guidelines in 2011 [39]. Furthermore, 2016 saw a peak in the number of publications, which may be related to the published SDGs, the 2030 Agenda, in 2015 [100]. After that, the number of yearly publications remains stable.

Based on the defined groups for the types of assessment in the studies, more than half of the publications can be allocated to Group 1. Furthermore, the first studies on sustainability assessment of roads developed frameworks for SRS (Group 2). However, in the following years, research focused more on the life-cycle-based methods.

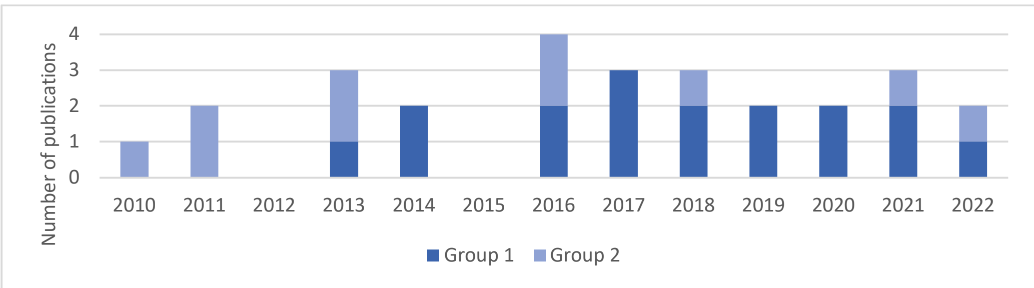


**Figure 3.** Publication years of the reviewed studies.

The country of affiliation of the first author was assessed to identify trends regarding the regions in which the sustainability assessment of roads is considered (Figure 4). Most of the studies were developed in North America (with more than half of the studies being developed in the United States of America), followed by Asia and Europe. The prominence of North America can be linked to efforts to advance the sustainability assessment of pavements, such as the development of an LCA framework for these structures [101].

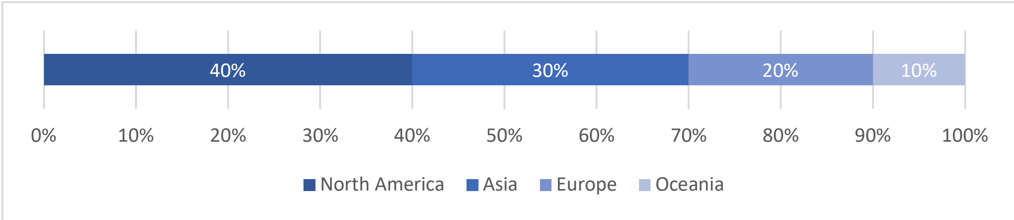


**Figure 4.** Country of affiliation of first author.

With a keyword analysis, the most important topics and content trends of the studies were identified. The results are presented in Figure 5. The keyword analysis indicated four clusters:

1. The first cluster is the biggest (14 items) and revolves around the words 'sustainability assessment' and 'decision-making', each with 10 counts. Surrounding these terms are the keywords 'road' (nine counts) and 'sustainability' (six counts). This cluster suggests a significant interest in integrating sustainability considerations into decision-making processes for road infrastructure.
2. The second cluster centers around the keywords 'asphalt' (seven counts), 'multi-criteria decision making' (six counts), and 'life cycle sustainability assessment' (six counts). Further terms in this cluster are 'asphalt pavement', 'sensitivity analysis', 'environmental management', and 'economic assessment' (three counts each). These keywords hint at a focus on evaluating asphalt pavements, considering multiple criteria, and using MCDM methods, including environmental and economic factors, within the sustainability assessment process. In this regard, MCDM methods are often chosen to enable the interpretation of LCSA results and/or rank proposed alternatives.
3. The third cluster is formed around the terms 'sustainable development' (with 13 counts) as well as 'life cycle' (nine counts) and 'life cycle assessment' (eight counts). These keywords are surrounded by the terms 'pavement' (six counts) and 'environmental impact' (five counts). This group indicates a strong connection between sustainability, life cycle thinking, and environmental considerations in pavement assessments. This cluster suggests a focus on evaluating the environmental performance of pavements and their contribution to overall sustainable development.
4. The fourth cluster (four items) revolves around the terms 'sustainable pavements' and 'decision support system' (three counts each), as well as 'eco-design' and 'mixtures' (two counts each). These keywords highlight the interest in developing environmentally friendly and sustainable pavement solutions.

There is also some overlapping among clusters. In particular, words from one cluster are connected to words from other clusters. An analysis of such words regarding their distance from each other proves to be particularly insightful since the distance between two keywords in the network indicates their relatedness [128]. For instance, the word 'decision-making' from the first cluster is closely related to the keywords 'life cycle assessment' in the third cluster and 'multi-criteria decision making' from the second cluster. The close relationship between 'decision-making', 'life cycle assessment', and 'multi-criteria decision-making' suggests that decision-making processes in road sustainability assessments often employ MCDM methods to consider multiple criteria or objectives. Additionally, the incorporation of Life Cycle Assessment indicates the integration of environmental considerations throughout the life cycle stages of roads and pavements. These approaches enable stakeholders to make informed decisions that account for a broader range of sustainability dimensions in road sustainability assessments. Furthermore, the word 'life cycle' of the third cluster is closely connected to the words 'sustainable pavements' of the fourth cluster and 'sustainability assessment' of the first cluster. These connections signify the consideration of the life cycle of (sustainable) pavements while carrying out sustainability assessment.

**Table 1.** Overview of publications on the sustainability assessment of roads and pavements.

| No. | Source | Group | Object | Country | Framework? | Case Study? | System Boundaries |
|---|---|---|---|---|---|---|---|
| 1 | [102] | Group 2 | Existing roads | Jordan | X | - | Not specified |
| 2 | [103] | Group 1 | Roads | Australia | X | X | Not specified |
| 3 | [104] | Group 1 | Roads | Pakistan | X | X | Construction, maintenance, and use, as well as the upstream processes and materials for each stage |
| 4 | [105] | Group 1 | Pavement and pavement activities | Not specified | X | X | All pavement activities |
| 5 | [69] | Group 2 | Highways | Germany | X | - | Complete life cycle |
| 6 | [106] | Group 1 | Pavement materials | China | X | X | Material production, transport, construction, use, EoL stages |
| 7 | [107] | Group 2 | Roads | United States | X | - | Not specified |
| 8 | [108] | Group 2 | Linear infrastructure projects | Spain | X | X | Complete life cycle |
| 9 | [109] | Group 2 | Future and existing roads | Europe and Turkey | X | - | Complete life cycle |
| 10 | [110] | Group 2 | Roads | Australia | X | - | Not specified |
| 11 | [111] | Group 2 | Highways | Iran | X | X | Not specified |
| 12 | [112] | Group 2 | Road infrastructure | Netherlands | X | - | Not specified |
| 13 | [113] | Group 1 | Pavement | Germany | X | X | Product, construction, use, and EoL stages |
| 14 | [114] | Group 1 | Pavement | United States | X | X | LCA: Material production, construction, maintenance/LCC: Construction, maintenance/S-LCA: Use |
| 15 | [115] | Group 1 | Roads | Iraq | X | X | Not specified |
| 16 | [116] | Group 1 | Pavement | United States | X | X | Material extraction and processing, transportation of pavement materials and ready-mixtures, asphalt mixing process, and construction |

**Table 1.** *Cont.*

| No. | Source | Group | Object | Country | Framework? | Case Study? | System Boundaries |
|---|---|---|---|---|---|---|---|
| 17 | [117] | Group 1 | Pavement | United States | X | X | Material extraction and processing, transportation of pavement materials and ready-mixtures, asphalt mixing process, and construction |
| 18 | [118] | Group 2 | Future and existing roads | United States | X | X | Design, supply chain processes, maintenance and preservation, roadway use, construction activities, material hauling, and production |
| 19 | [119] | Group 1 | Roads | Canada | X | X | Not specified |
| 20 | [120] | Group 1 | Urban street (including pavement, sidewalks, islands, pavement marking and striping) | United States | X | X | Production of materials, transport of materials, electricity use during operation (lighting), EoL (removal of pavement, transport of pavement to landfill) |
| 21 | [121] | Group 1 | Transport infrastructure | Europe | X | X | Raw material extraction and mixture production, construction and maintenance and rehabilitation, traffic management, use, and EoL |
| 22 | [122] | Group 1 | Highways | United States | X | X | Not specified |
| 23 | [123] | Group 1 | Rural unsealed road pavements | Australia | X | X | Construction, operation, and maintenance |
| 24 | [124] | Group 2 | Transport infrastructure | Not specified | X | - | Not specified |
| 25 | [125] | Group 1 | Pavement | China | X | X | Raw materials, production, construction, and maintenance |
| 26 | [126] | Group 1 | Pavement | China | X | X | Raw materials and production, construction, use, and maintenance |
| 27 | [127] | Group 1 | Pavement | Not specified | X | - | Material extraction and manufacturing, construction (equipment operation), use (rolling resistance, albedo, lighting), maintenance (equipment operation) |

X denotes that the element is present.

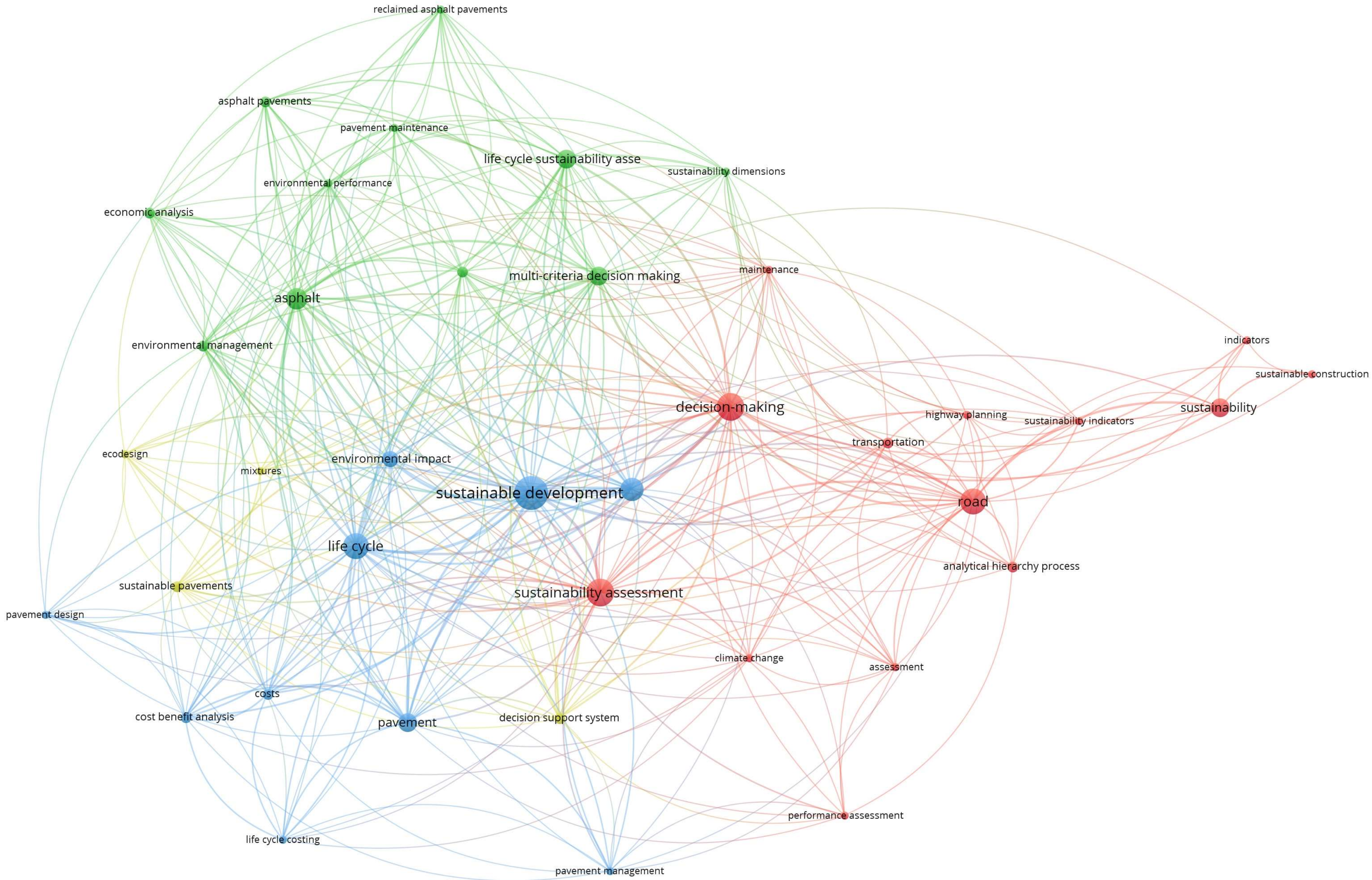


**Figure 5.** Network visualization of the main keywords.

### 4.2. Assessment Results

The selected publications were assessed regarding the type of pavements being evaluated (Figure 6). None of the studies focused on exclusively rigid pavements, while nearly 50% examined flexible pavements. Furthermore, several studies compared the sustainability performance of flexible and rigid pavements. One study considered unsealed roads, while 30% of the studies did not specify the type of pavement for which the described or proposed framework was intended.

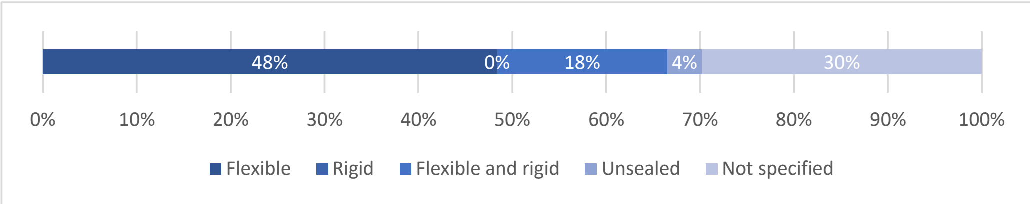


**Figure 6.** Pavement typologies.

With regards to the type of project considered in the studies (Figure 7), many of the frameworks and case studies addressed already existing projects (33%), while an equally large group did not specify whether new or existing (or both) projects were the object of the assessment. This aspect is particularly relevant given the objective pursued and the indicators chosen, together with the quantity and quality of data available for the evaluation.

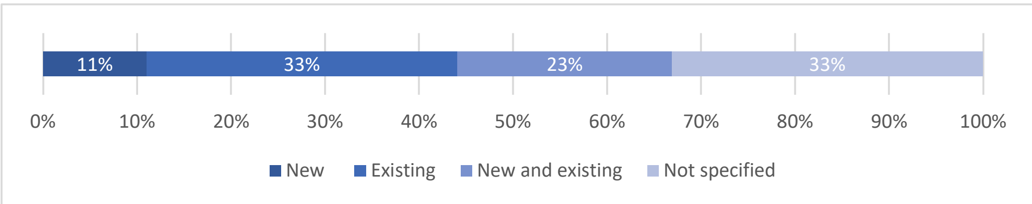


**Figure 7.** Project type.

#### 4.2.1. Life-Cycle-Based Methods (Group 1)

Seventeen publications were assigned to Group 1, which included LCSA frameworks or similar approaches based on the TBL. First, the goals of the studies were reviewed. In this regard, nearly 70% of the studies aimed to compare material or project alternatives. The second most common goal was to support decision makers in different aspects of projects, for example, to select maintenance alternatives [105,114,115,127]. Other studies aimed to develop LCSA-based frameworks to monitor the sustainability performance of projects. Finally, one of the studies focused on promoting sustainable development.

A total of 47% of the studies did not disclose an FU. Most of the studies that did specify one relied on road dimensions only. In particular, the length of the road/pavement was the FU. The rest of the studies provide an FU based on surface dimensions, either explicitly (e.g., 1 $m^2$) [106] or implicitly (e.g., length and width of the road) [113,114,125,126]. Only one FU included the period of analysis. Several studies included other characteristics of the assessed object. However, these were not directly linked to the FU. None of the studies considered a parameter for road quality or function. One study only expressed the FU for the LCC. Thus, it was unclear if the results of the environmental and social assessments were based on the same unit [113]. Furthermore, two studies defined an FU for the LCA and LCC but assumed that the social impacts are not connected to an FU [125,126].

An analysis of the system boundaries was carried out based on the information modules defined by standard EN 15804 [53]. Because different authors often used different terminology to refer to the life cycle stages, the use of the standard as a reference supported the creation of an overview of the system boundaries to identify common points and differences. According to this norm, the life cycle of a product consists of five parts:

- Product stage: Raw material extraction (A1), transport to the production site (A2), and production (A3);
- Construction stage: Transport to the construction site (A4) and construction (A5);
- Use stage: Use (B1), maintenance (B2), repair (B3), replacement (B4), refurbishment (B5), operational energy use (B6), and operational water use (B7);
- EoL stage: Deconstruction or demolition (C1), transport (C2), waste treatment (C3), and landfill (C4);
- Benefits and loads beyond the product system: Reuse, recovery, and/or recycling potential (D).

The included life cycle stages of the studies are depicted in Table 2. Most of the reviewed studies assessed the product and construction stages. There was just an exception of a study that did not incorporate the product stage [123]. Four of the seventeen studies did not disclose the system boundaries.

**Table 2.** System boundaries (based on EN 15804).

| Source | Life Cycle Stages according to EN 15804 | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | A1 | A2 | A3 | A4 | A5 | B1 | B2 | B3 | B4 | B5 | B6 | B7 | C1 | C2 | C3 | C4 | D |
| [106] | X | X | X | X | X | X | X | - | - | - | - | - | X | X | X | X | - |
| [103] | * | * | * | * | * | * | * | * | * | * | * | * | * | * | * | * | * |
| [105] | * | * | * | * | * | * | * | * | * | * | * | * | * | * | * | * | * |
| [113] | X | X | X | X | X | - | - | X | X | - | - | - | X | X | - | - | - |
| [115] | * | * | * | * | * | * | * | * | * | * | * | * | * | * | * | * | * |
| [120] | X | X | X | X | X | - | - | - | - | - | X | - | X | X | - | x | - |
| [121] | X | X | X | X | X | X | X | - | - | X | - | - | X | X | X | X | - |
| [122] | * | * | * | * | * | * | * | * | * | * | * | * | * | * | * | * | * |
| [123] | - | - | - | - | X | X | X | - | - | - | - | - | - | - | - | - | - |
| [104] | X | X | X | X | X | X | X | - | - | - | - | - | - | - | - | - | - |
| [114] | X | X | X | X | X | X | X | - | - | - | - | - | - | - | - | - | - |
| [119] | * | * | * | * | * | * | * | * | * | * | * | * | * | * | * | * | * |
| [125] | X | X | X | X | X | - | X | - | - | - | - | - | - | - | - | - | - |
| [126] | X | X | X | X | X | - | X | - | - | - | - | - | - | - | - | - | - |
| [127] | X | X | X | X | X | X | X | - | - | - | - | - | - | - | - | - | - |
| [116] | X | X | X | X | X | - | - | - | - | - | - | - | - | - | - | - | - |
| [117] | X | X | X | X | X | - | - | - | - | - | - | - | - | - | - | - | - |

X denotes that the life cycle stage was included in the system boundaries. * System boundaries were not specified in the study. - Not included.

For more clarity, the proportion of studies assessing the different life cycle stages is seen in Figure 8. Generally, the construction stage was the life cycle portion included in most studies, closely followed by the product stage. Moreover, more than half of the studies assessed the use stage. The EoL was the least examined stage considered in about 25% of the studies. In addition, the burdens and credits beyond the product system (module D) were not assessed by any studies, although the production and use of secondary raw materials in the context of road construction (e.g., through Reclaimed Asphalt Pavement, RAP) is a common practice in many countries. The omission of modules C and D can be related to several reasons. For instance, Zheng et al. [126] referred to the long service life of roads and the uncertainty of what happens at the EoL. Furthermore, roads are not usually decommissioned but are modified and further utilized at the end of their planned service life, making it challenging to define a specific point for the EoL and the beginning of a new life cycle.

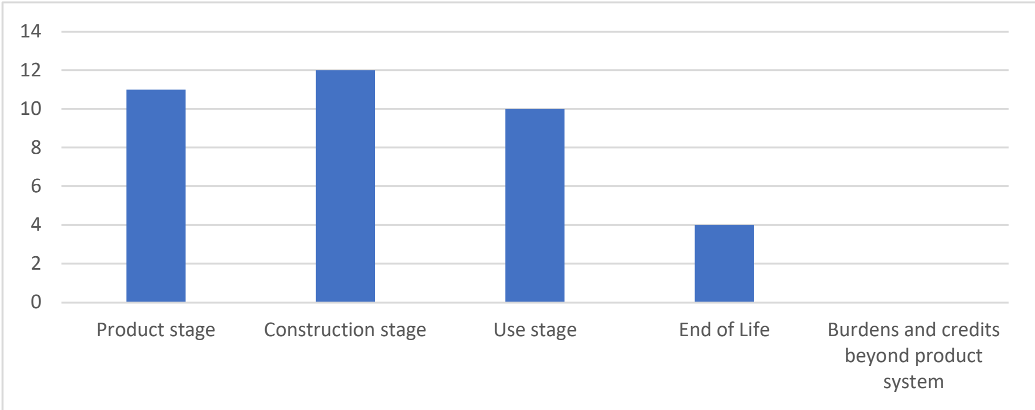


**Figure 8.** Life cycle stages included in the 17 reviewed studies.

As previously mentioned, the use stage was widely assessed. This stage comprises different activities. A closer look at the use stage showed that the most included activity in this life cycle stage was maintenance (B2), closely followed by use (B1) (Figure 9). The operational water use (B7) was not assessed in any of the cases, as this module does not seem to be relevant to roads and pavements. Only one study considered operational energy use [120] since it focused on urban roads with lighting.

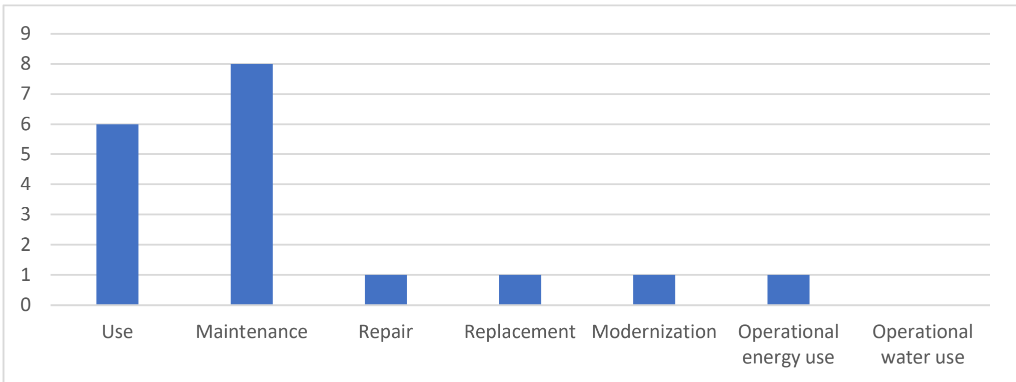


**Figure 9.** Activities considered in the use stage by the reviewed studies.

Environmental Dimension

An overview of the main characteristics of the environmental assessment is provided in Table S1. The evaluations were conducted using LCA in all cases with two different approaches: process LCA (referred to as LCA in Table S1) and Economic Input–Output (EIO) LCA. The latter was adopted by two studies.

Although LCA is a highly standardized method at a general level and in the construction industry, most studies did not refer to any standard or guidelines. Only five studies stated which standard or guideline was used as a reference. In most cases, the references were ISO 14040 [129] or ISO 14044 [104,106,113,114,126,130]. Only one study referred to the standards EN 15804 and prEN 17392 [113]. Zheng et al. [126] used the UNEP/SETAC guidelines for their study, which refers to ISO 14040 and ISO 14044.

LCA is a data-intensive method that requires relevant, high-quality data. In this regard, the lack of data generated limitations in some studies. For instance, Kadhim et al. [115] had to limit the number of indicators due to this issue. In Group 1, more than 50% of the studies relied on secondary data from databases, reports, and the scientific literature. The databases were not always disclosed, but some mentioned are the Chinese Life Cycle Database, Ecoinvent, and NONROAD 2008. In addition, mathematical models were used in some cases to estimate emissions during material extraction, manufacture, and transport (e.g., Greenhouse gases, Regulated Emissions, and Energy use in Technologies, GREET), emissions of vehicles (MOtor Vehicle Emission Simulator 2014, MOVES 2014), and air emissions during the use stage (MOBILE 6.2). Three studies used a combination of primary and secondary data. Some examples of primary data are the results of field studies measuring traffic volume or monitoring pavement conditions and bills of quantities. Only Zheng et al. [125] addressed the topic of data quality, which was assessed using a Data Quality Indicator (DQI). The DQI considers the aspects of reliability, completeness, temporal correlation, geographical correlation, and other technological correlations [125].

Around 70% of the studies did not state the software for calculating the environmental impacts. Among the studies that disclosed this information, SimaPro© [131] was the most used. ECO-Comparator was used in one study [105]. Finally, one study did not disclose the software used in the case study, but SimaPro©, GaBi© [132], and OpenLCA© [133] were suggested as alternatives.

The indicator analysis yielded several findings. First, the studies are very heterogeneous regarding the number of impact categories assessed, ranging from 1 to 13 impact categories. Second, most studies examined the environmental impacts at the midpoint level. The only exception was Arshad et al. [104], who conducted an assessment using the endpoint indicators of ReCiPe 2016 [134]. The use of endpoint impact categories can be associated with the communication of results to decision makers and audiences with no LCA background since the results are expressed in terms of 'areas of protection', which are usually easier to understand for a general audience. However, using midpoint indicators may be more suitable for identifying hotspots and optimizing measures. Finally, although some studies did use an LCA approach to evaluate the environmental dimension, no impact assessment was performed. Instead, only emissions were reported, indicating misuse of terms. In other words, although it may seem that an LCA took place, only a (partial) LCI was conducted.

The reported indicators could be categorized into three groups: midpoint indicators, endpoint indicators, and other indicators. Endpoint indicators present the results for the areas of protection damage to human health, damage to the ecosystem, and damage to resource availability [134], while midpoint indicators evaluate the environmental impacts at a certain point between the emission and the endpoint [135]. Some indicators could not be assigned to the defined groups, mainly because these are not typical LCA indicators, and no definition was provided. As depicted in Figure 10, most reported indicators were midpoints. Among these, it is evident that GWP was the most used indicator, followed by Acidification Potential (AP), Energy Use, Eutrophication Potential (EP), and Photochemical Ozone Creation Potential (POCP).

For some indicators, it was unclear in which form these were reported. For instance, Bryce et al. [105] differentiated between aquatic and terrestrial acidification, while none of the other studies that considered AP did not provide further specification. Moreover, the assessment of some indicators was also heterogeneous. For example, regarding Energy Use, one of the studies referred to non-renewable energy consumption [105], while in another study, the total primary energy demand was reported [113]. Furthermore, the indicator of Human Health was usually disaggregated into cancer, non-cancer, and criteria air pollutants. However, some studies investigated only Human Health—criteria for air pollutants [114,125,126]. Another example is the indicator of Water Use. One study reported Water Withdrawal [116], while another reported Water Intake [119].

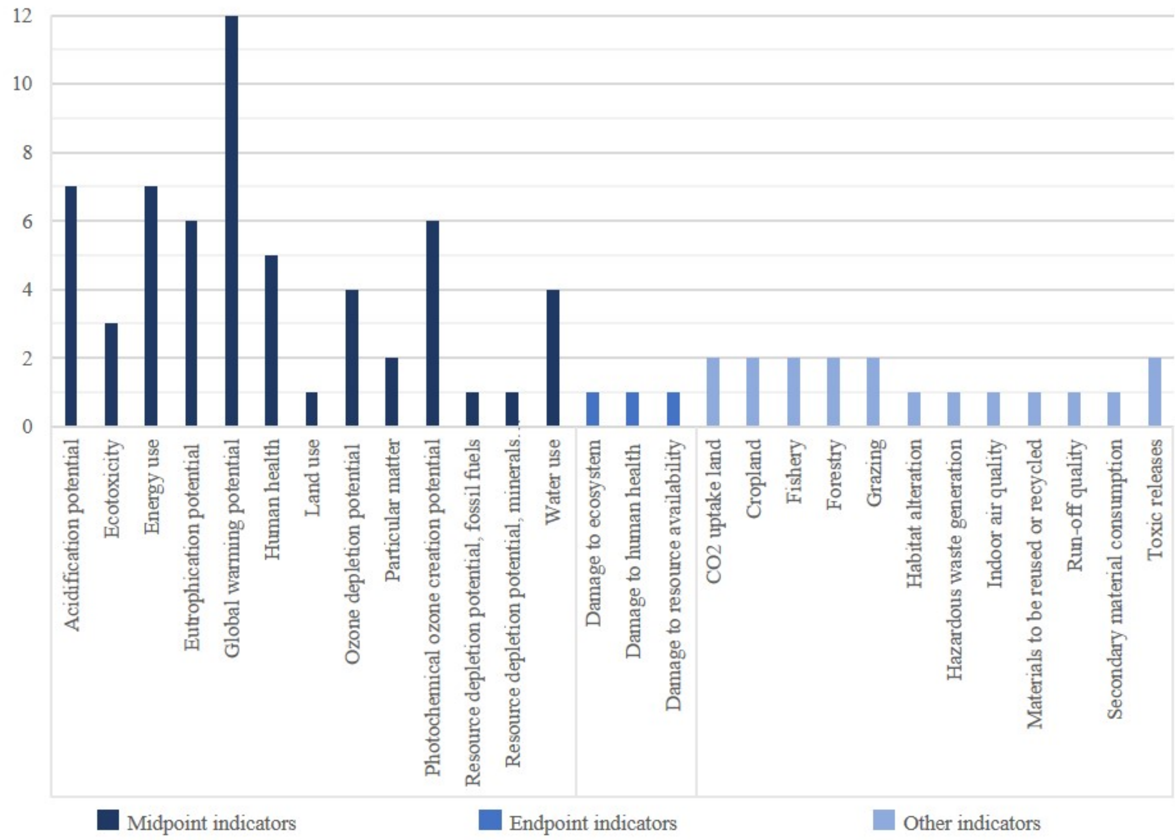


**Figure 10.** LCA indicators.

Among the studies that carried out an impact assessment (12 in total; 2 studies applied EIO-LCA, and 3 studies did not perform LCIA), 6 reported the LCIA method. The most used one was 'Tool Reduction and Assessment of Chemical and other environmental Impacts' (TRACI) [136]. In those studies, either the case study took place in North America or the first author was affiliated with a North American country. Furthermore, the methods ReCiPe (Endpoint 2016 and hierarchist) [137], CML 2001 [138], and Cumulative Energy Demand (CED) were applied.

Only one study communicated the implemented allocation method—cut-off [106]. This was one of the two studies that considered the complete EoL module (C1–C4). Finally, only three studies conducted a sensitivity analysis. In one of the cases, the sensitivity analysis was performed considering the combined results and will not be discussed in this section. The authors of [113] performed a sensitivity analysis based on the service life of asphalt layers with additives and the production temperature of additive-modified asphalt. Kucukvar et al. [117] considered the rate of the additives, the distance of materials to mixing sites, and the amount of mixing energy.Economic Dimension

The main characteristics of the approaches to evaluate the economic dimension in the different studies are presented in Table S2 (Supplementary Materials). The economic assessment was conducted in most cases using LCC. One study applied CBA [106]. LCC and CBA differ from each other in several aspects, one being the fact that LCC is a comparative assessment tool, while CBA is generally used to evaluate projects independently [139]. The authors used CBA to consider the costs for the initial construction and maintenance of the pavement alternatives and to monetarize the environmental (GWP) and social (noise reduction benefit) impacts. Furthermore, Kucukvar et al. [116] and Kucukvar et al. [117] used a TBL-LCA EIO framework to evaluate economic impacts. Tatari et al. [122] used an approach based on the expansion of economic opportunity and the increased value of transportation assets achieved as a consequence of the improvement of road-based transport of goods and the quality maintenance of the roads [122].

Similar to the environmental dimension, most studies did not disclose which standards or guidelines were used as references. The ones cited were the standards EN 15643-4 (currently withdrawn) and ISO 15686-5 (for buildings), the guidelines UNEP/SETAC (for LCSA), the code of practice for environmental LCC [41], the cost breakdown by the American Society for Testing and Materials, and general bids and authorities' guidelines. In the case of the CBA, the Cost–Benefit Guidelines of the European Commission were adopted as a reference.

The cost categories of the assessments were considered (Figure 11). Most studies focused on agency costs (i.e., organization costs). In particular, several studies addressed construction and maintenance costs (59% and 53% of the studies, respectively). For the material costs, it was not always clear if transport costs were included. Furthermore, construction costs may or may not cover material costs, crew fees, and/or equipment costs, but this was also not always disclosed. One study makes a general mention of the agency costs [121]. Since it was unclear which costs were meant exactly, this mention was accounted for separately. Concerning the costs of road users, the Vehicle Operating Costs (VOCs) are the most assessed. Kadhim et al. [115] introduced the cost category Estimated Revenues, defined as savings in VOCs and Travel Time Costs (TTC). Regarding externalities, environmental damage costs for carbon and noise reduction benefits were quantified in two and one studies, respectively.

Since costs are highly stakeholder-dependent, it is important to communicate which stakeholders are covered in the economic assessments. This aspect is also relevant for a possible comparison of results. Therefore, it was investigated if the covered stakeholders were disclosed. This information was not specified in more than 50% of the studies. Most studies that reported the stakeholder groups opted for assessing the costs of both the road agency and users. The rest examined only the road agency costs. No study evaluated road user costs exclusively.

Regarding the type of data used, 7 out of the 17 studies relied on secondary data sources such as reports, statistics, and literature, while 6 studies did not disclose what types of data were used. Furthermore, three studies used a combination of primary and secondary data, and only one study used primary data exclusively. As for the performance of the analysis, not many studies disclosed what kind of software was used. In one case, Microsoft Excel was used, while in a further two cases, the software RealCost 2.5 of the U.S. Federal Highway Administration (FHWA) was used [140]. Santos et al. [121] suggested four alternatives: HCM, RealCost, QUADRO, and Visum.

An analysis of the indicators showed that most studies relied on one indicator for assessing the economic impacts (Figure 12). Most studies choose the Net Present Value (NPV). An exception was one study where the life cycle costs were determined without applying a discount rate [119]. Furthermore, five of the studies opted for the assessment of several economic indicators. For instance, Alam et al. [103] suggested the calculation of the NPV and the Cost–Benefit Ratio (CBR), although in their case study, only NPV was determined. Tatari et al. [122] used the Truck Throughput Efficiency (TTE) and the Pavement Condition Score (APC). Kucukvar et al. [116] and Kucukvar et al. [117] used the Gross Operating Surplus (GOS), Import, and Tax as indicators in their TBL-LCA EIO framework. Finally, Kadhim et al. [115] used a combination of NPV, BCR, and Internal Rate of Return (IRR) to evaluate the economic impacts.

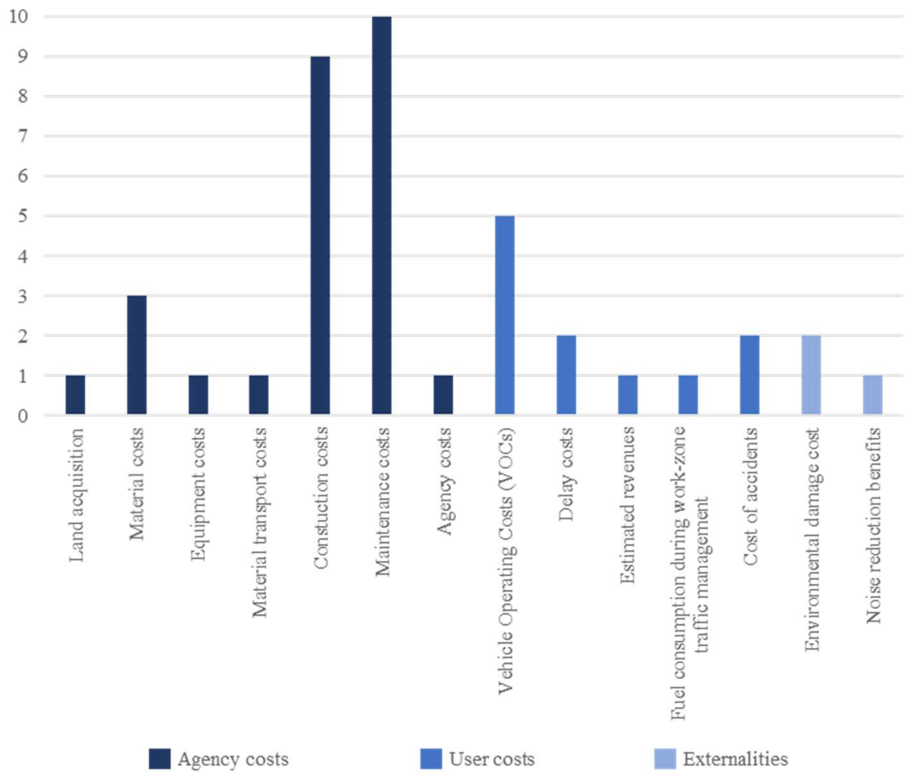


**Figure 11.** Cost categories included in the economic assessments of the reviewed studies.

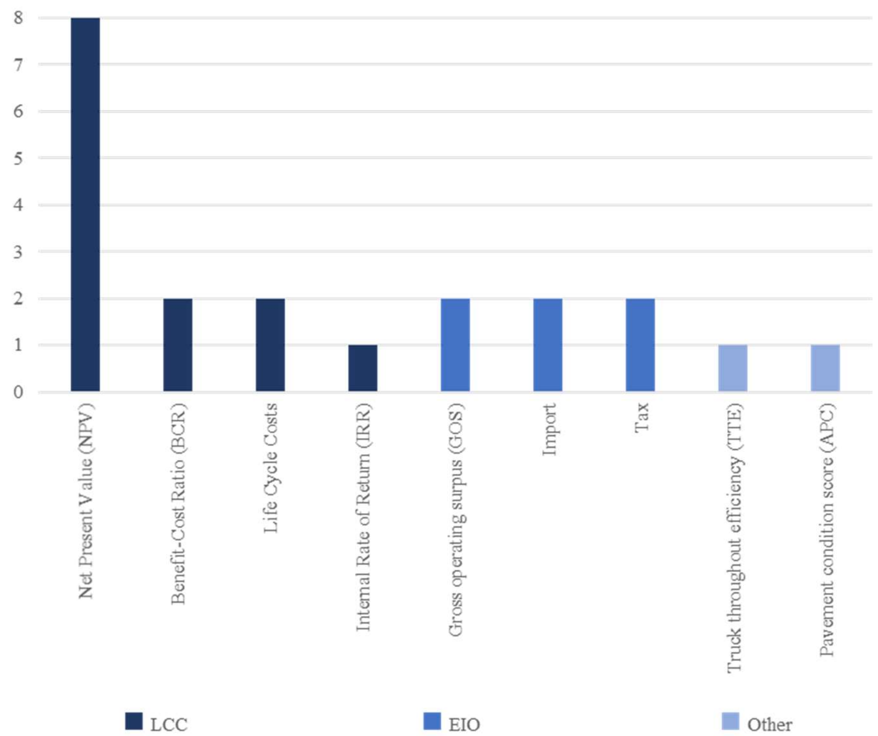


**Figure 12.** Indicators assessed in the economic assessments of the reviewed studies.

Social Dimension

The main characteristics of the social evaluations are presented in Table S3 (Supplementary Materials). Their examination showed that less than half of the studies applied S-LCA. In turn, 53% of the studies relied on selected social indicators not (explicitly) connected to S-LCA. Similar to the previously analyzed dimensions, the reference standard or guideline for the applied methodology was often not disclosed. For the studies applying S-LCA, the Guidelines for S-LCA [141], the Product Social Impact Assessment (PSIA) handbook [142], the UNEP framework for LCSA [39], and the ISO 14040 [129] were cited as references. In those studies not applying the S-LCA method, other references were used. Kadhim et al. [115] used the international Road Assessment Program (iRAP) methodology to estimate road fatalities and serious injuries (FSI) [143]. Santos et al. [121] referred to Directive 2008/96/EC on road infrastructure safety management to define the indicator 'safety audits and safety inspections' [144] and to the CNOSSOS-EU method for strategic noise mapping for the indicator 'noise reduction' [145].

The evaluation of social impacts depends on the considered stakeholder category. In most cases, the studies addressed more than one stakeholder, except Kadhim et al. [115], who only dealt with the stakeholder category of Consumers, and Cao et al. [106] and Inti [114], who analyzed the local community stakeholder category. Figure 13 evidences that the most included stakeholder categories are the local community and consumers, followed by workers, society, and value chain actors. None of the studies addressed the stakeholder category of children. A possible reason for this omission is the fact that the impacts on children in the context of road pavements are not different from the impacts on the local community.

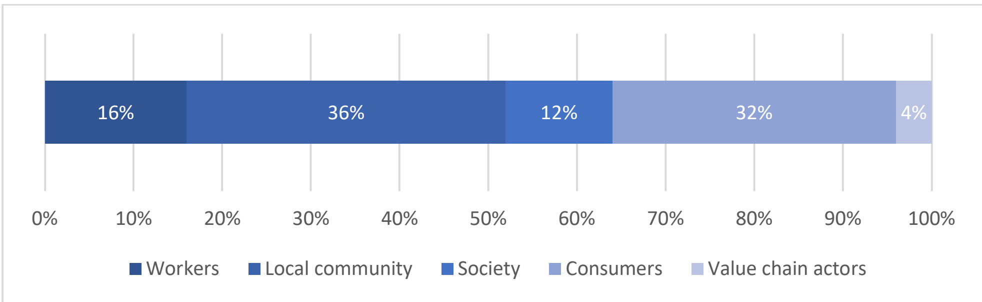


**Figure 13.** Stakeholders addressed.

Regarding the data sources, most studies relied either on a combination of primary and secondary data or on secondary data exclusively. Primary data were obtained from the respective project records, field visits or questionnaires, and surveys. Secondary data came from databases, such as the Social Hotspot Database (SHDB) [146], national statistics, reports, and papers. Moreover, most studies did not disclose the software used for the social assessment, except for two cases. Kadhim et al. [115] used the iRAP method to assess FSI, while Patel and Ruparathna [119] used SimaPro© for S-LCA.

Among the studies that performed an S-LCA, the evaluated sub-categories were examined and aggregated for the different stakeholder groups (Table 3). Consistent with the analysis of the included stakeholders, the greatest number of sub-categories were evaluated for the groups of local community and consumers.

Finally, the social indicators were examined. Most reviewed studies included several indicators, ranging from 2 to 16. Of the studies assessing a single indicator, only one conducted S-LCA [114]. Two studies do not disclose the used indicators but the impact categories [104,119]. Table 4 presents the indicators addressed and allocated to the corresponding stakeholder categories of the UNEP Guidelines for S-LCA, regardless of whether S-LCA was applied or not. Not all indicators were assessed within the respective studies that proposed them, either because of a lack of data or because no case study was performed. Thirty indicators were identified. Of these indicators, 13 were quantitative, 15 were semi-quantitative, and 2 were qualitative.

**Table 3.** S-LCA sub-categories.

| Stakeholders of Guidelines for S-LCA | Sub-Categories |
|---|---|
| Workers | Working hours |
| | Health and safety |
| | Professional growth |
| Local community | Safe and healthy living conditions |
| | Respect for indigenous rights |
| | Community engagement |
| | Local employment |
| | Secure living conditions |
| | Contribution to economic development |
| Society | Prevention and mitigation of armed conflicts |
| | Technology development |
| Consumers | Health and safety |
| | Feedback mechanism |
| | Transparency |
| | Access to material resources |
| | Access to immaterial resources |
| | Delocalization and migration |
| | Cultural heritage |
| Value chain actors | Fair competition |
| | Promoting social responsibility |

**Table 4.** Social indicators.

| Stakeholders of Guidelines for S-LCA | Indicators | Type | Sources |
|---|---|---|---|
| Workers | Exposure of workers to vapors and aerosols during construction | Quantitative | [113] |
| | Safety audits and safety inspections | Qualitative | [121] |
| | Per month average working hours | Quantitative | [125,126] |
| | Management of overtime hours | Semi-quantitative | [125,126] |
| | Preventive and emergency measures for daily work injuries | Semi-quantitative | [125,126] |
| | Management efforts of occupational diseases | Semi-quantitative | [125,126] |
| | Training courses | Semi-quantitative | [125,126] |
| Local community | Noise reduction | Quantitative | [106,121] |
| | Construction noise | Quantitative | [105] |
| | Traffic noise | Quantitative | [105,114] |
| | Health and discomfort issues caused by increase in dust | Quantitative | [123] |
| | Use local material resource | Semi-quantitative | [125,126] |
| | Management efforts to minimize air and noise pollution | Semi-quantitative | [125,126] |

**Table 4.** *Cont.*

| Stakeholders of Guidelines for S-LCA | Indicators | Type | Sources |
|---|---|---|---|
| Society | Obligation on public sustainability reporting | Semi-quantitative | [125,126] |
| | Usage rate of new technology | Semi-quantitative | [125,126] |
| Consumers | Annual crashes/mile (ACM) | Quantitative | [122] |
| | Crash risk reduction<br>Savings in FSI from road rehabilitation and upgrading | Quantitative | [105,116] |
| | Increase in accidents caused by increase in roughness, dust, and the reduction in friction | Quantitative | [123] |
| | Work-zone traffic congestion<br>Time lost due to queuing at construction or maintenance | Quantitative | [105,121] |
| | Travel time index | Quantitative | [121] |
| | Management effort to keep IRI | Semi-quantitative | [126] |
| | Education/outreach | Qualitative | [105] |
| | Comfort (drivers) | Quantitative | [121] |
| | Dedicated bike lanes | Semi-quantitative | [120] |
| | Parking spaces for cars | Semi-quantitative | [120] |
| | Bicycle racks | Semi-quantitative | [120] |
| | Sidewalks and crosswalks | Semi-quantitative | [120] |
| | Outdoor patio seating during summer months in local businesses | Semi-quantitative | [120] |
| | (Impression of) More open space for pedestrians | Qualitative | [120] |
| | Use of high-reflectivity paint | Semi-quantitative | [120] |

In most cases, the safety and wellbeing of the road users (consumers) and the local community included the topics of noise (from construction or traffic), road safety (accidents), and comfort. In this regard, most indicators were semi-quantitative and quantitative. Only three of these studies considered the stakeholder category of workers, focusing on health and safety [113,123]. Society was the stakeholder category with the smallest number of indicators, which addressed public sustainability reporting and the use of new technology. Out of 15 studies, 6 conducted an S-LCA. Among those six studies, only three addressed society as a stakeholder group. The reasons for not assessing the impacts on society are not always clear. However, it is theorized that the neglect could be connected to the approach used to assess the social impacts. As mentioned above, when assessing the social dimension, most studies relied on selected indicators instead of applying a systematic method for the assessment, as it was done for the environmental and economic dimensions. The reason for this might be missing or limited knowledge of S-LCA as a method for quantifying social impacts. As a result, an assessment is conducted that focuses, in most cases, on one stakeholder only, delivering limited results. Furthermore, the inclusion of society in the assessment is limited by data unavailability and the complexity of quantifying the impacts [114], as well as the use of certain databases and software for carrying out the analysis.

Integration and Interpretation Approaches

The result integration and interpretation for the three dimensions were analyzed (Table S4, Supplementary Materials). Most studies made an integrated interpretation of the results, meaning that the results of each dimension were analyzed in a combined way. There were two exceptions. Bryce et al. [105] did not specify whether or not the results of the three dimensions were to be assessed together. Reddy et al. [120] analyzed the results of the three dimensions separately.

In the studies conducting a combined interpretation of the results, several different approaches were followed that can be aggregated into four groups. The first group comprises studies in which a sustainability index is developed—Road Sustainability Index [103], LCSA value function [104], Green Road Score [119], Highway Sustainability Score [122], and Integrated Sustainability Degree (ISD) [125]. The indexes by [103,119] propose a similar approach, as seen in Equation (1).

$$Sustainability\ Index = Score_{env} \times W_{env} + Score_{econ} \times W_{econ} + Score_{soc} \times W_{soc} \quad (1)$$

where $Score_{env}$, $Score_{econ}$, and $Score_{soc}$ are the scores (results) of the environmental, economic, and social assessments, respectively. $W_{env}$, $W_{econ}$, and $W_{soc}$ are the weights of the assigned to the environmental, economic, and social dimensions, respectively.

The Highway Sustainability Score from Tatari et al. [122] is the ratio of the economic impacts to the social and environmental impacts. This ratio maximizes positive impacts (represented in this study by the economic impact (improved freight transport and maintained road quality)) and minimizes negative impacts (depicted by the social (travel time and annual crashes) and environmental impacts (emissions and noise)). The ISD from Zheng et al. [125] incorporates a weighted combination of the results with a probabilistic approach to account for uncertainty.

The second group corresponds to the studies applying MCDM methods. Kucukvar et al. [116] used a combination of these methods: Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to select the best pavement alternative, intuitionistic fuzzy entropy to identify the importance of stages and criteria, intuitionistic fuzzy weighted geometric averaging operator to establish a sub-decision-making matrix based on weights of attribute, and intuitionistic fuzzy-weighted arithmetic averaging operator to build a super decision matrix depending on weights of different life cycle phases. Kucukvar et al. [117] used the Compromise Programming Model to seek the solution closest to the ideal point, and Santos et al. [121] used the PROMETHEE-II method to rank the different alternatives based on their sustainability performance. Zheng et al. [126] used the *VIseKriterijumska Optimizacija I Kompromisno Resenje* (VIKOR) method to identify compromise alternatives, while Zheng et al. [127] used TOPSIS for the ranking of alternatives.

The third group comprises studies that analyze the trade-offs among sustainability dimensions. Holldorb et al. [113] focused on savings achieved through the assessed alternatives compared to a baseline scenario for all dimensions and possible trade-offs generated. Kadhim et al. [115] also focused on the trade-offs between sustainability dimensions. Furthermore, the authors suggested aggregating the results into an index. However, this was not carried out in their study. Finally, van Wijk et al. [123] considered the influence of selected parameters in the defined sustainability indicators.

The last group includes studies using different approaches that cannot be assigned to the already described groups. Ref. [106] recurred to a monetarization of the results (as described in the sections for environmental and social assessments). Inti [114] ranked alternatives based on weights assigned by consulted decision makers. Finally, Bryce et al. [105] developed a sustainability-based decision support system that builds on the DPSIR (Driver, Pressure, State, Impact, Response) framework. The DPSIR framework was originally proposed by the European Environmental Agency for the assessment of environmental impacts [147]. Bryce et al. [105] adapted the DPSIR framework to the three sustainability dimensions with a performance management framework.

Concerning weighting methods, some studies did not use any weights at all. Those who did define weights applied various approaches. Among the reviewed studies, AHP appears to be an established method [104,114,125–127]. Further methods examined established rating systems for roads [103] and the orientation of the priorities of the local governments [119]. Kucukvar et al. [117] used entropy based on the opinion of the decision makers, which was evaluated using fuzzy linguistic terms, while Tatari et al. [122] used Data Envelopment Analysis (DEA). In two cases, the weights within the environmental dimension are based on the weights of the Building for Economic and Environmental Sustainability (BEES) framework.

The average weights assigned to the different sustainability dimensions are as follows: 32% for the environmental, 37% for the economic, and 31% for the social dimensions. For the environmental dimension, the lowest weighting was 8% [114], while the highest was around 70% [121]. The lowest weight assigned to the economic dimension was approximately 10% [121], and the highest was 54% [114]. In the social dimension, the lowest weight was assigned by Inti [114] at 10%, while the highest one was assigned by Patel and Ruparathna [119] at 45%.

Finally, the visualization approaches were examined. Nine out of seventeen studies did not provide a visualization of the combined results. Studies that did visualize the results mostly used bar charts, but different information was provided. Alam et al. [103] presented their results for each investigated alternative in bar charts with the results for each dimension and the sustainability indexes (with two different weighting sets). Similarly, Tatari et al. [122] used a bar chart to show the sustainability index of the assessed alternatives. The bar chart from Cao et al. [106] showed the monetarized results for each option, indicating the portion of the total costs of each dimension (investment cost, environmental damage cost, and noise reduction benefit). Kucukvar et al. [117] used a bar chart showing the most appropriate allocation of pavement alternatives based on different sets of weights for the sustainability dimensions—that is, the visualization is not of the assessment results but of the measures that can be taken based on the results of the sustainability assessment. Van Wijk et al. [123] used a bar chart to show the relative difference in the outcomes compared to a defined baseline scenario. The results are shown for each assessed indicator. Finally, Zheng et al. [125] showed the frequency distributions of their sustainability index for the studied pavement alternatives.

In contrast to the previous studies, Ref. [113] used pie charts to present the results for the environmental and economic dimensions (the social dimension was not visualized) for each variant. In this regard, a disaggregation based on road structure (surface, binder, and base layers) was chosen [113]. Moreover, Inti [114] presents their results in a radar chart with the ranking of the different alternatives done by decision makers. Similar to Kucukvar et al. [117], the visualized results are not those of the assessment itself.

#### 4.2.2. Sustainability Rating Systems (Group 2)

Table S5 (Supplementary Materials) presents the characteristics of the SRS collected in the review. Similar to Section 4.2.1, the goals of the studies were analyzed and categorized into different focus areas. The largest area (27%) comprises studies generally focusing on promoting sustainable development. Other common focus areas (18% each) are project performance monitoring and decision-making support. The rest of the studies focused on comparing material and project alternatives, harmonizing the process for the sustainability assessment, and implementing sustainable practices. The final 9% of the studies did not specify their goal. Only two of the presented rating system approaches are currently in application [112,118].

Table S5 also presents an overview of the criteria structure, categories with their corresponding weighting, and evaluation procedure. Regarding the structure, in most cases, these are presented in a two- or three-tier structure. In other words, there is an assessment at a 'lower' level using indicators, which can be aggregated into a higher level—e.g., in 'sub-categories' as in Al Hazaimeh and Alnsour [102], in 'macro-indicators' as in Fernández-

Sánchez and Rodríguez-López [108] or in 'principles' as in Heeres et al. [112]—or into the highest level of assessment, i.e., 'categories'. Gunarathna et al. [110] followed a similar approach by adopting a five-tier structure that links specific performance measures to indicators. The indicators are, in turn, connected to specific objectives and more general goals, while the goals are classified within five 'sustainability dimensions'. In the various papers, the 'categories' are referred to as 'themes'', 'sustainability dimensions', 'sustainability aspects', or 'first-grade indicators'. This assessment level usually corresponds at least to the dimensions of sustainability and may also address other topics, such as technical performance and process quality. For more clarity and in the context of SRS, the term 'categories' is used in this review to refer to the highest level of assessment.

In the categories covered, all sustainability dimensions (environment, economic, and social) are represented either in an explicit (the name of the sustainability dimension is mentioned directly) or implicit way (the name of the sustainability dimension is not mentioned, but aspects that can be associated to it are). Furthermore, all studies included the environmental dimension explicitly, while the economic and social dimensions were considered explicitly in nine and eight cases, respectively. In the implicit consideration, aspects related to mobility, participation, access, and equity were highlighted. Moreover, many studies included technical aspects in their assessment [69,102,107,109,110,118]. In this regard, aspects such as planning, leadership, innovation, construction activities, and pavement technologies were addressed.

Regarding the evaluation of the results, many studies assign a score and weight to their indicators, which are then aggregated into higher levels of assessments, as explained above, until a final score is obtained for the whole evaluation. Based on this, a performance level may be assigned, such as level A–D [102] or certified, silver, gold, and evergreen performance [118]. Dhakal and Oh [107] present the final result on a 100-point scale. Fernández-Sánchez and Rodríguez-López [108,110] and Zhang et al. [124] develop sustainability indicators based on the weights assigned to the different categories. Another evaluation approach is proposed by Heeres et al. [112]. Standardized questions are defined (instead of indicators) to assess whether a positive or a negative impact has been generated by the project. Based on the answers to the questions, a sustainability score is determined and visualized in a so-called 'synergy wheel'.

The SRS indicators are presented in Table S6 (Supplementary Materials) and allocated to different topics. In total, 280 indicators were collected. The indicators of the SRS are a combination of different approaches. Several of them measure the performance of the road, e.g., by assessing the amount of local materials used or the $CO_2$ emissions generated. In turn, other indicators focus on depicting what could be perceived as 'best practices', such as implementing dust control measurements during construction, performing safety audits, or using a certain type of material (e.g., recycled or local). For this latter group, no information is provided that justifies that the promoted practices are more sustainable or beneficial than other measures. The indicators were allocated to the different sustainability dimensions. Regarding the environmental dimension, indicators were identified for biodiversity, climate mitigation and adaption, environmental impacts, land use, resource and energy consumption, and waste. In the social dimension, the addressed areas are accessibility (to the structure and to information), adaptability, comfort and user amenities, cultural heritage, education, health and safety, impacts on the local community and society, innovation, and public engagement. The economic dimension focuses on the topics of costs, economic profit, and finance. Finally, several indicator groups could not be allocated to the sustainability dimensions. These indicators are related to technical or operational aspects of roads, such as design, maintenance activities, management, mobility, soil and earthwork, stormwater, and traffic.

In the environmental dimension, the most covered area was resource and energy consumption, with 40 indicators. The indicators focus on energy consumption and savings, use of renewable energy, material consumption, use of local and recycled materials, and water efficiency and quality. Furthermore, the use of certain products and materials was encouraged (e.g., sustainable wood, permeable materials, and warm-mix-asphalt). Another topic often addressed is environmental impacts, with indicators for air quality, emissions of materials and equipment, and water pollution. Additionally, several studies encouraged the use of LCA or environmental footprinting [107–109,118]. Biodiversity was a relevant topic in several SRS, focusing on biodiversity protection, barrier effect, and habitat creation, protection, and loss. In the social dimension, the most assessed topics are comfort and user amenities, impacts on the local community, and health and safety. In comfort and user amenities, the SRS address the designation of bicycle and pedestrian paths, aesthetics, and appropriate lighting. Most indicators measuring the impacts on the local community focused on noise quantification and reduction of light pollution. Health and safety are centered mainly on road users (i.e., accidents), although some indicators do address the safety of workers. In the economic dimension, most indicators revolved around the project's LCC and CBR. Finally, several indicators focused on management-related topics, such as compliance with the project budget or the presence of management plans (e.g., environmental, pavement management, strategic, quality management, etc.).

## 5. Discussion

In this review, several questions arose regarding sustainability assessment in the context of roads and pavements. These questions were introduced in Section 1 and are discussed below.

1. Have TBL-based assessments been used to evaluate the sustainability performance of roads?
   The systematic review found 27 studies in which a sustainability assessment framework based on the three dimensions was proposed or applied in case studies. The first paper appeared in 2010, shortly after the first publications on the LCSA method [33,34]. From 2016 on, a stable trend in the number of publications can be recognized, with at least two studies per year. This outcome is in line with the findings of Backes and Traverso [76].
2. What approaches are followed for assessing the sustainability impacts of roads considering the three dimensions of sustainability?
   A closer analysis of the selected studies showed that two approaches were used to assess the sustainability performance of roads and pavements. On the one hand, Group 1 comprises all collected studies applying LCSA or a combination of life-cycle-based methods. On the other hand, Group 2 is composed of studies with a sustainability assessment framework based on SRS. Around 60% of the reviewed studies were allocated to Group 1. The first study from this group was published in 2013—3 years after the first recorded sustainability assessment in this review, which corresponds to Group 2. SRS are already well known and widely used in the building sector [67]. Therefore, it is reasonable that the first road assessments adopt the format of SRS (Group 2). From Group 1, around 35% of the studies attempted to conduct a complete LCSA (i.e., LCA + LCC + S-LCA). The remaining studies address the social dimension without applying the S-LCA method. Instead, indicators considered to be relevant were selected based on the literature or experience. The environmental assessment was almost exclusively done with process LCA, except for two studies that adopted an EIO-based approach. In the economic dimension, three approaches were identified, LCC, CBA, and TBL-LCA based on EIO, of which the first one was the most widely used. The studies in Group 2 defined categories and sub-categories that included selected indicators. Many of these studies did not only address the sustainability dimensions known from the TBL but also included technical aspects in the assessment, which is a notable difference from LCSA and life-cycle-based methods. Furthermore, all studies of Group 2 assigned a score and weights to their indicators and categories.

3. How were the life-cycle-based methods applied?
To answer this question comprehensively, it was subdivided into different aspects guided by the questions below and based on the approaches and outcomes presented in the studies of Group 1.
    (a) Was the framework proposed by Kloepffer [33] and Finkbeiner et al. [34] followed?
    Roughly 35% of the studies of Group 1 proposed or carried out an LCSA, i.e., LCA, LCC, and S-LCA. However, these approaches differ from the concept proposed by Kloepffer by assigning weights to the different dimensions. The weighting of LCSA results could be detrimental since practitioners may try to compensate for poor performance in one dimension with better performance in another [33]. Nevertheless, weights may support interpretation considering the circumstances and priorities of a particular geographical context. For instance, Santos et al. [121] assigned the highest weight to the environmental dimension in their French case study, while Arshad et al. [104], Inti [114], Patel and Ruparathna [119], Zheng et al. [126], and Zheng et al. [125], with case studies in Pakistan, United States, Canada, and China, gave priority to the economic dimension. Moreover, weightage could support the communication and comprehension of results for decision makers without a background in sustainability assessment.
    In all cases of the Group 1 studies, LCA and LCC (or variations of both) were conducted. This finding confirms the expectations of the authors since these methodologies are widely used for the assessment of buildings and infrastructure projects, even in the context of SRS, such as Level(s), *Deutsche Gesellschaft für Nachhaltiges Bauen* (DGNB), and LEED, to name a few examples [148–150]. However, S-LCA was not as commonly adopted, appearing only in six studies. This lack of application arises from challenges such as the low maturity of the method and data availability [151].
    (b) What standards and guidelines are used as a reference?
    Most studies did not reference the used standards or guidelines. For LCA, the ISO 14040 was cited in four studies [104,106,113,114]). The ISO 14040 and the ISO 14044 (also cited as a reference by one study) provide the general principles and framework, as well as the requirements and guidelines for conducting LCA in general. Zheng et al. [126] cited the LCSA framework of the UNEP as the reference guideline. Only Ref. [113] used norms specific to the sector—EN 15804 and prEN 17392. Both standards provide core rules for developing Environmental Product Declarations (EPD), EN 15804 for construction products in general, and prEN 17392 for asphalt mixtures. The latter standard has been withdrawn as of 2023. For LCC, Ref. [113] was the only study to refer to construction-related standards—EN 15643-4 and ISO 15686-5. Other references cited were Cost Breakdown by the American Society for Testing and Materials, the Cost–Benefit Guidelines of the EU-Commission (as seen in Cao et al. [106]), bids and authorities' guidelines (as seen in Santos et al. [121]), as well as the UNEP LCSA guideline and the LCC code of practice (as seen in Zheng et al. [126]). For S-LCA, the UNEP guidelines [141] were the most cited document, which was expected since this is one of the few documents that guide S-LCA. Furthermore, the iRAP methodology [115], Directive 2008/96/EC on road infrastructure safety management, the CNOSSOS-EU method for strategic noise mapping [121], and the ISO 14040 [127] were also cited.
    Several documents are available that provide guidelines for LCA, LCC, and S-LCA at different levels of specificity and with different scopes. Furthermore, in the cases of EN 15804, EN 15643-54 (withdrawn), and ISO 15686-5, the scope comprises only buildings, although they have been used as a reference for roads. Since there is not a clear set of standards specifically for road

and pavement assessment, a wide margin remains for potentially subjective decisions regarding methodological aspects. In this regard, specific properties of roads are not considered, such as their long service life or the incorporation of recycled material in the assessment. This degree of freedom is detrimental to comparability. As observed in this study, it was not possible to compare the assessment results with each other. Due to the relative approach of LCSA and life-cycle-based methods, it is crucial to be able to compare assessment results.

(c) What are the goals of the studies?
In most studies, the goal was the comparison of materials or project alternatives. Moreover, some studies intended to support decision makers in the selection of materials and maintenance alternatives. These objectives evidence the importance and urgency of developing specific guidelines for performing LCSA on roads and pavements. Robust comparisons can only be made if a set of rules fixing all methodological choices has been defined. These rules should guide aspects related, for example, to the definition of the FU and data quality. Furthermore, frameworks are needed that support decision-making by providing results in a comprehensible way.

(d) What FUs are used?
The review showed that almost half of the studies did not explicitly disclose the chosen FU. Most studies that specified an FU addressed only one parameter, which was usually length or surface. Only one study provided more detailed information, such as surface, layer thickness, and period of analysis [106]. In total, three different FU were identified in the studies. Per definition, the FU should provide the quantified performance of a product system, acting as a reference unit [19]. Therefore, the length or surface of the road section alone is insufficient. More details are necessary to define the performance of roads and pavements. For the definition of a suitable FU, the approach proposed by the Product Environmental Footprint (PEF) method can be helpful. According to this method, an FU provides information regarding what function or service is provided, how much of that function or service is considered, how well the service or function is provided, and how long the product is used [152]. For the case of roads and pavements, the exercised function (what) can be linked to the type of road (e.g., freeway versus local street) or pavement (e.g., flexible versus rigid). The 'amount' of service (how much) can be then linked to the length, surface, or even the cross-section of the road, while the quality of the function (how well) can be connected to the load class of the road. Finally, the time component of the FU (how long) is linked to a defined period of analysis.

(e) What life cycle stages do the studies address?
The construction stage was the most assessed among the reviewed studies, closely followed by the product and use stages. In sustainability assessments, however, it is more common that the product stage is the most widely evaluated, as demonstrated by Del Rosario et al. [67]. In this review, the product stage was not accounted for in five studies—in four of them, there was no disclosure of the assessed life cycle stages, while in the other, the focus lies on the vehicles and machinery used in the pavement activities. Furthermore, the use and maintenance stages were prioritized in several of the reviewed studies. The relevance of the use stage in the sustainability performance of roads has already been addressed in the literature. For instance, Araújo et al. [153] demonstrated that the energy consumption and the generated GHG and NOx emissions in the use stage of roads could be significantly higher than in the construction stage (700 and 1000 times, respectively). In turn, only a few studies addressed modules C and D (EoL and burdens and credits beyond the product system). As mentioned in Section 4.2.1, the exclusion of these modules

might be related to the high uncertainty in the definition of scenarios or the challenging definition of the end of the road's service life. However, neglecting these life cycle stages may lead to an under- or overestimation of the impacts of roads due to possible relevant aspects or credits being neglected. Moreover, with a growing focus on the circularity of materials and product systems, it is important to assess the sustainability effects of EoL strategies.

Further analysis of the results also showed that the evaluated life cycle stages changed based on the assessed sustainability dimensions. Specifically, although the product stage was addressed in most studies in the environmental assessment, it was not included, or at least it was unclear if it had been considered, for the economic and social impacts. Something similar occurs with the material and equipment transport to the construction site. In addition, the EoL is entirely neglected in the economic and social assessments. Moreover, concerning the economic dimension, many studies referred to 'initial costs' when describing the cost categories that were analyzed. However, it was not detailed if this included the material acquisition and transport or the construction activities. Furthermore, in both the economic and social assessments, the most considered stages were the construction and use stages, followed by the maintenance stage.

(f) What types of data were used in the assessments regarding sources and quality?

For the environmental dimension, the reviewed studies relied mainly on secondary data sources, such as databases, mathematical models for emission estimation, and reports. In the case of the economic and social assessments, most studies combined primary and secondary data sources. Only one study used primary data exclusively, namely for the economic assessment.

LCSA is a data-intensive method, and depending on when it is carried out (e.g., construction stage versus planning or design stages), more or less information may be available. Data availability may also be affected by the dissemination and robustness of the methods and indicators used for the evaluation. For instance, the importance of environmental assessment is becoming more evident for construction companies due to policy regulations [154]. The companies are then either motivated or required to generate environmental data. Furthermore, LCA is a highly standardized method, and it is more likely to find data for it, either primary (directly from companies) or secondary (e.g., from databases). In turn, S-LCA is a novel method still under development. Especially in the construction sector, few studies have been performed, and even fewer stakeholders (e.g., companies and road agencies) are familiar with S-LCA. Therefore, the data sources for social assessment are limited. However, some studies assessing social impacts without the framework of S-LCA (usually focusing on noise or accidents) reported using primary data.

(g) What indicators were used?

Regarding the environmental dimension, most studies used midpoint indicators for the assessment. Among these, GWP was the most used indicator. This finding is consistent with the outcomes of other SLR on LCA in the building and road construction sectors [23,24,30,31,155]. Furthermore, GWP is commonly used by companies and governments to measure their environmental performance [156]. Further used indicators are AP, Energy Use, EP, and POCP. In addition, indicators such as Land Use, Particular Matter, Resource Depletion—Fossil Fuels, and Resource Depletion—minerals are rarely assessed, although these are issues that could be relevant for roads.

Regarding the economic assessments, most studies relied on NPV to express the results. This finding is consistent with Babashamsi et al. [157] and Moins et al. [21], who signaled NPV as one of the most used indicators for LCC. NPV quantifies all relevant costs and benefits of roads in one value [158]. However, this aggregation can only be done if all alternatives are subject to the same period of analysis [21]. Furthermore, some reviewed studies suggested the calculation of the BCR [103,115]. However, Walls and Smith (1998) advise against it due to challenges in sorting out costs and benefits. Kucukvar et al. [116] and Kucukvar et al. [117] applied indicators at the level of economic sectors. Therefore, the assessment level (sector level versus project level) should be considered when selecting indicators for an economic assessment.

Among the social indicators, there was a high degree of heterogeneity. Therefore, conclusions could not be drawn regarding which were most widely applied. However, in most cases, semi-quantitative (15) and quantitative (12) indicators were chosen. Only three indicators were qualitative. Furthermore, most indicators were allocated to the stakeholder category of consumers (road users) and focused on road safety (accidents), travel time, and comfort. Especially for this stakeholder group, the differentiation among road types is critical to identify the most relevant indicators. In this regard, only one of the indicators was proposed in the context of an S-LCA. This shows that although road users are recognized as relevant in the social assessment of roads and pavements, they are neglected in S-LCA. In contrast, the stakeholder group society was only considered in the context of S-LCA.

(h) How are the results interpreted (combined or separately)?

Most studies in this review attempted an integrated interpretation of the outcomes, i.e., analyzing the results of the sustainability dimension in a combined way. This consideration of the results is consistent with the recommendation of interpreting the LCSA results integrating the three dimensions [34,39]. Most authors opted for the weighted aggregation of the results in a sort of sustainability index or the application of MCDM, either for ranking alternatives or for selecting the nearest alternative to an ideal solution. The wide adoption of MCDM methods is consistent with the findings of Alejandrino et al. [38]. These findings contrast with the LCSA concept of Kloepffer [33]—which stated, as aforementioned, that the weighting of results should be avoided. One of the reasons for applying weights relates to the concept of “weak sustainability”, in which the improvements in one dimension can compensate for the impacts on another dimension [159]. However, as pointed out by Finkbeiner et al. [34], it is necessary to acknowledge that different goals are to be achieved and diverse criteria are to be addressed in various contexts, inevitably leading to implicit weighting. Therefore, the best option is to assign these weights transparently and scientifically. Furthermore, assigning weights and aggregating results may be beneficial for understanding the outcomes and making decisions from the proper perspective [159].

(i) What methods were used for the visualization of results?

The visualization methods of the sustainability assessment or LCSA outcomes are very heterogeneous. Many authors opted to present their aggregated results in bar charts. This type of visualization might be valuable for obtaining an overview of the results. However, a very coarse aggregation of results can also hinder the identification of specific hotspots. Furthermore, the visualization approach should support the understanding of the results and decision-making [160]. In this regard, it may be appropriate to show results for each dimension and life cycle stage, among others. Several authors have proposed various visualization methods for LCSA results, such as the Life Cycle Sustainability Triangle [34], Life Cycle Sustainability Dashboard [161], Pareto optimization graphs [162], and LCSA-Wheel [163], to name some examples. However, none of these approaches are specific to the road construction sector. Depending on the assessment scope and the stakeholders involved, it might be necessary to visualize the assessment results for each road layer or road component.

4. If other approaches were used for the sustainability assessment, how were they applied?
As detailed in the answer to Question 2, this review showed that SRS-based assessments (Group 2) were also used to evaluate roads and pavements. These frameworks comprise a series of categories in which the three sustainability dimensions are represented. Criteria and indicators are assigned to each category and are then scored and weighted. One of the main issues found with these frameworks is the lack of consistency in how they are structured (two-, three- or five-tiered structure). Furthermore, the different types of topics addressed, the type of criteria and indicators used, and how the scoring is performed affect the comparability of outcomes.

5. What are the main challenges identified?
While LCA and LCC in their different variants, as well as the simultaneous combination of these two methods, are widespread, also in the context of roads as studied by several authors [88–92], this literature review showed the small number of studies focusing on the holistic sustainability assessment of roads and pavements. This finding evidences the lack of dissemination not only of LCSA but also of the TBL approach. Furthermore, social assessment is often neglected in the road sector since only a few stand-alone S-LCA studies exist in the literature [22,164]. This finding is consistent with similar observations in the construction industry [165]. Less than half of the reviewed publications applied S-LCA to assess social impacts. The rest of the studies relied on one or several indicators to evaluate certain impacts associated with the social dimension but outside the framework of an S-LCA. In this regard, it is crucial that a structured method, such as S-LCA, is used to evaluate social impacts. S-LCA enables the consideration of all relevant stakeholders and the consistent application of a life cycle approach equivalent to LCA and LCC. Moreover, only a few of the reviewed studies considered the stakeholder category of workers, although relevant construction sector issues include workers' working conditions and health and safety [165]. In the reviewed studies, workers were only considered during the construction stage. Their involvement in other relevant life cycle stages, such as maintenance and renovation or during the production of the pavement materials, was not addressed, or at least not explicitly indicated. As a result, the social impact assessment of roads and pavements has several gaps—the failure to consider critical stakeholders and the omission of relevant life cycle stages. These gaps are further intensified by the lack of a structured method for assessing social performance since a clear picture of all relevant impacts cannot be achieved. Given that S-LCA is a novel method in comparison to LCA and LCC, the road construction sector could benefit from sector-specific guidelines or standards guiding the implementation of S-LCA. Furthermore, the conduction of social hotspot analysis to identify the most critical social topics within road-related economic sectors would be a manageable but effective first step towards a complete S-LCA.
Concerning the system boundaries, the review evidenced that many studies defined different boundaries for each sustainability dimension. Based on the work of Kloepffer and UNEP on LCSA, the nature of the different methods (LCA, LCC, and S-LCA) sometimes does not allow for defining identical system boundaries for all dimensions [39]. For example, although processes during the raw material extraction are relevant for LCA and S-LCA, in LCC, the cost of these processes may be less relevant, whereas the price of the final product (e.g., asphalt) is the relevant one. Nevertheless, system boundaries should be drawn as consistently as possible, considering the detail or aggregation level required for each method to guarantee that all relevant inputs and outputs are captured.
Although LCSA and the combination of life-cycled-based methods are considered more suitable for sustainability assessment, this review showed how many studies

neglected or did not disclose several methodological aspects. For instance, in many studies, the FU, the system boundaries, or indicators were not clearly defined. For the studies that did provide these parameters, several issues were observed, as discussed in Question 3.

Regarding SRS, these are already well-known and widely used tools in the building sector [67]. Due to the inherent differences between buildings and roads, the existing systems for buildings cannot be directly applied in the context of roads without modifications. Furthermore, SRS present some disadvantages, such as high complexity and extensiveness, leading to the need for additional resources for their implementation. Additionally, SRS do not necessarily evaluate the whole life cycle of a project, allowing certain aspects to be neglected or shifted to another life cycle stage. Moreover, the sustainability assessment is not conducted as thoroughly as in an LCSA. Many criteria in SRS require implementing certain practices considered more sustainable than 'business as usual'. The issue with this practice is twofold: (1) the criteria are not based on measurable indicators, and (2) no evidence is provided as to whether or not the suggested practice is more sustainable for the assessed project.

The two identified assessment approaches (life-cycle-based methods and SRS) highlight the lack of harmonization for the sustainability assessment. Even among these different methods, several disparities could be observed. This lack of harmonization hinders comparability among the outcomes of sustainability studies. This issue is long-known within sustainability assessment in general and the construction industry [166,167]. This aspect has already been addressed by Hoxha et al. [23] in the context of road and pavement LCA. Hence, defining harmonizing frameworks and standards at general and sectorial levels is essential for developing and disseminating sustainability assessment.

*Limitations of the Study*

This SLR attempted to provide a comprehensive overview of how sustainability assessment is conducted for roads and pavements. Despite the authors' best efforts, some limitations restricted the scope of this work. In this regard, two databases were selected for the retrieval of studies. Although they were considered comprehensive, relevant studies might not be indexed in them. Therefore, to reduce the risk of neglecting relevant literature, a snowballing approach complemented the PRISMA statement. In addition, the research included entries in English, German, and Spanish—studies in other languages could not be considered. Moreover, this review focused on roads and pavements only. Other structures, such as bridges and tunnels, were not part of the scope of this review. Another limitation is connected to the content of the studies. In particular, no comparison of the outcomes of the assessment was conducted. This decision is related to the aspects addressed in Question 5, i.e., lack of harmonization and comparability. Due to differences in the FU, scope, system boundaries, assessment methods, indicators, and interpretation methods, no comparisons could be carried out.

## 6. Conclusions

This study focused on TBL-based assessments for the sustainability assessment of roads and pavements. An SLR was conducted that identified publication trends of the studies in this field. Most evaluations were performed using life-cycle-based methods such as LCA and LCC combined with selected social indicators and LCSA. Furthermore, most studies were conducted in North America and Asia, highlighting the need for more studies in other geographical contexts.

The review showed that two main approaches were used to evaluate the holistic sustainability performance of roads and pavements: life-cycle-based methods (Group 1) and SRS (Group 2). The analysis of the studies in Group 1 showed that only a few studies applied LCSA for the assessment. Furthermore, challenges that affect the comparability of the outcomes were uncovered, such as heterogeneity in the definition of FU, system boundaries, indicators, impact assessment methods, cost categories for the economic assessment, and stakeholder categories in the social assessment, among others. Moreover, differences in the system boundaries among the three dimensions in the different studies were also observed. Most studies conducted an integrated interpretation of the outcomes. In this regard, the studies performed a weighted aggregation of the results in sustainability indices or applied MCDM. Regarding the studies in Group 2, a common structure was identified following the approach of SRS. In all studies, the three sustainability dimensions were assessed, while some authors included aspects related to planning, leadership, innovation, construction activities, and pavement technologies in their assessments.

The SLR evidenced few studies focusing on holistic sustainability assessment of roads and pavements. Several methods and approaches were identified, which prevented comparing the outcomes. Even among studies following the same or similar methods, a comparison of the results was not possible due to their methodological choices. Furthermore, the review evidenced inconsistencies in the social assessments. In particular, many different stakeholders and indicators were addressed in the studies. Therefore, a structured method assessing the social impacts of roads, such as S-LCA, is needed to obtain consistent and robust results.

Most identified challenges in this review can be connected to the lack of a harmonized approach for the sustainability assessment of roads. Due to its comprehensiveness in terms of the life cycle approach and consideration of the TBL concept, LCSA is considered a promising method that can provide robust outcomes that support the optimization of the sustainability performance of roads. However, standards and frameworks for the assessment of roads are needed. In the case of standardization, several norms exist already for LCA at general (ISO 14040 and ISO 14044) and sector (EN 15804) levels. Nevertheless, these norms are not specifically tailored for road pavements and provide a wide margin for their own interpretations and assumptions, leading to the heterogeneity of approaches evidenced in this SLR. Something similar occurs for LCC, where the only available standard caters to buildings (ISO 15686-5). As for S-LCA, a standard is currently under development (ISO 14075). This norm will be the equivalent of the general standards for LCA, meaning that specific aspects related to road pavements (or any other sort of possible application), such as particularities of the supply chain, possible data sources, and data collection methods, will not be addressed. Due to the characteristics of road pavements (e.g., very long service life, multifunctionality, a great number of stakeholders involved) and the complexity of life-cycle-based methods, the road construction sector would benefit from dedicated standards guiding the implementation of LCA, LCC, and S-LCA. As for LCSA, a specific framework for roads is needed to guide and promote its application in this sector. Such a framework should address the gaps identified within this SLR. Therefore, further work in those areas is urgently needed for the operationalization of LCSA in the road construction sector. An example of an aspect that needs to be studied is the definition of a meaningful FU that properly expresses the particular characteristics, functions, and performance of roads and can support comparative assertions if needed. Furthermore, consistent system boundaries, indicators, and impact assessment methods (for the environmental and social dimensions) must be appointed. In this regard, the specific hotspots connected to roads (and everything they entail) in terms of life cycle stages, processes, and impact categories must be identified and considered. Moreover, how the results are to be interpreted (e.g., which MCDM method, which weights) must also be defined under consideration of the involved stakeholders and how the decision-making processes for this sort of project work. The insights gained in this study could indeed support the development of such a framework.

Finally, a further important topic to be addressed in future work relates to the connection of sustainability goals (e.g., at a national level) and the sustainability performance of roads, as briefly mentioned in Section 1. In particular, the potential contribution of roads to the achievement of sustainability goals should be assessed. The identification of said contribution can support an efficient use of resources and efforts towards the most relevant impacts. Furthermore, these goals can function as guidance to establish priorities and as a benchmark by which to relate the measured performance.

**Supplementary Materials:** The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su152115654/s1. Table S1: Characteristics of the environmental assessments carried out in the reviewed studies; Table S2: Characteristics of the economic assessments carried out in the reviewed studies; Table S3: Characteristics of the social assessments carried out in the reviewed studies; Table S4: Integration approaches and result interpretation of the three sustainability dimensions in the reviewed studies; Table S5: Characteristics of the sustainability rating systems proposed or presented in the reviewed studies; Table S6: SRS indicators.

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