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Life Cycle Assessment of Sustainable Road Networks: Current State and Future Directions

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Abstract: The construction sector is one of the leading global contributors to environmental footprint, with road infrastructures being a significant resource consumer. The traditional practice of using virgin raw materials and extracting natural aggregates has a significant impact, causing landscape alterations and disruptions to ecosystems. As result, the focus on achieving sustainable mobility through road networks is increasing. Companies operating in the civil sector must consider the environmental performance of roads to inform their decision making. Various assessment tools are available, with life cycle assessment being a commonly employed methodology in the industrial sector. However, its application to infrastructure projects has inherent challenges, primarily due to the complexity associated with inventory management. This complexity has resulted in a limited adoption of LCA within this sector. This research explores the suitability and compatibility of existing tools, methodologies, and databases, while establishing future requirements to adapt LCA and other types of environmental analysis to the life cycle of roads. To achieve this objective, a comprehensive analysis of the scientific and technical literature is conducted in this study. The findings highlight the need for more versatile impact analysis tools, including specialized databases tailored to the specifics of road infrastructure. Such enhancements would facilitate the application of procedures outlined in ISO 14040 and ISO 14044 standards.

Keywords: life cycle assessment; roads; infrastructures; sustainable transport; environmental impact assessment; life cycle costing; climate change

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1. Introduction

The construction sector is currently a major contributor to global environmental impacts, accounting for 34% of global energy consumption and 37% of carbon dioxide emissions in 2021. This represents approximately one-third of the greenhouse gases emitted worldwide. Roughly 10% of the emissions from the construction sector come from the production of building materials, such as concrete, steel, aluminum, bricks, and glass [1,2]. At the end of the life cycle, buildings and other construction projects generate 100 billion tons of waste, of which approximately 35% is landfilled [3]. Specifically, road construction consumes significant amounts of resources and has a high environmental impact. In particular, the global expanse of transport networks currently encompasses 14 million km of land [4], and projections indicate an expected 60% growth from 2010 levels, which could result in an additional 25 million km of road networks by 2050 [5,6].

The construction of roads still relies mainly on virgin raw materials and the extraction of natural aggregates, which can damage the landscape and disrupt the ecosystem [7]. This practice continues even as there is a growing movement toward the utilization of waste materials that demonstrate comparable or superior performance to traditional resources [8]. In addition, substantial environmental impacts are related to the consumption of fossil fuels and energy, as well as the emission of greenhouse gases associated with road services, including lighting, drainage, electricity, and telecommunications.

These impacts include direct damage to the ecosystem (fragmentation and alteration of habitats, changes in water flow patterns, noise, artificial light, pollution, and effects on wildlife). Furthermore, roads indirectly contribute to climate change, the depletion of fossil fuels, and adverse effects on human health, among other consequences. Finally, during the operational phase, road transport also contributes to environmental impact. In the EU-28, 852.3 million tons of CO_2 were emitted in 2015 [1,9]. Furthermore, approximately 30% of small particles, which are the leading cause of death and illness related to air pollution, were attributed to road transport [10,11]

This circumstance has elevated the environmental control of road transport networks to an important position among the challenges faced by sustainable mobility. It currently stands as a top priority in the research and innovation programs' roadmaps for the horizon of 2030. The objectives are a 20% reduction in greenhouse gas emissions compared to 1990 levels, a 20% increase in energy efficiency, and a target of sourcing 20% of energy consumed from renewable sources. To achieve these goals, the European Union is developing regulatory environmental requirements for the transport sector to achieve a balance between economic interests and environmental protection.

This involves implementing an environmentally friendly approach during the project's inception and embracing a holistic life-cycle perspective. This approach ensures that solutions aimed at preventing and mitigating impacts are not limited to the operational phase, but also extend to include considerations for extraction of raw materials, product manufacturing, the construction process, operational phase, maintenance activities, and end-of-life. This strategy will facilitate the identification of the most significant factors and enable the ranking of sustainable designs to lower carbon emissions, minimize water usage and energy footprint, and mitigate habitat disruption. Furthermore, in the coming years, governmental authorities could demand carbon impact requirements (related to greenhouse gas emissions) and new certifications for construction (as EPDs or environmental product declarations). This development will further advance green public procurement (GPP) practices [12], contributing significantly to the goal of reaching carbon-neutral transport by 2050.

In this context, civil engineering plays an important role. Companies in the sector must evaluate the environmental performance of roads to inform decision making. Adopting sustainable strategies not only mitigates environmental impact and reduces resource consumption [13], it also contributes to the advancement of the circular economy by managing waste from other industry sectors [14]. For example, industrial by-products can be used to stabilize the road [15], repurposing of municipal ash from incineration [7,16] or incorporating plastic waste [17] into road and pavement construction.

To evaluate these sustainable solutions, various environmental analysis tools are available, including life cycle assessment (LCA) [18]. Although LCA is extensively used in the industrial sector, its application in the analysis of civil infrastructure is not straightforward. Assessing the life cycle impact of roads is challenging due to the variety of stages and unit processes involved as well as the materials and products from different manufacturers and suppliers. The scarcity of databases and specialized tools adds complexity when LCA is applied to roads. Furthermore, transparency, heterogeneity, and assumptions considered in existing studies continue to hinder the identification of the best sustainable solutions [19].

To meet the need for a systematic and quantitative approach to incorporate LCA into road projects, this article conducts a comprehensive review of the scientific literature and evaluates the tools, methodologies, databases, and software related to LCA. The main objectives are to explore the current state-of-the-art in LCA methodology applied to road infrastructure. This includes: (1) evaluating ongoing research efforts in this domain within the scientific community; (2) determining the availability of technical and digital resources for practical use in companies; and (3) outlining the key research directions and addressing the associated challenges. These objectives aim to address the research aim of understanding the predominant challenges associated with applying LCA in the road construction sector.

In the scientific literature, several reviews can be found within this research area. However, most of them focus on the application of LCA as a tool to assess the environmental impact of construction materials, particularly on pavement [20–27]. Studies that evaluate LCA utilization for specific stages of the road life cycle [28], investigate particular impact categories such as GHG emissions [29], or identify research gaps [30], research trends, and challenges to harmonization [19] are less common. In addition, there are notable works that, although not primarily focused on LCA, analyze indicators to assess road sustainability [31], the use of life cycle cost analysis [32], or life cycle-based risk assessment [21]. In contrast to previous publications, this work explores the applications of LCA in roads, from the first publications to the most recent (1988–2023). It distinguishes between applications that encompass the entire life cycle of the road and studies with narrower scopes (including analyses of specific stages, components, and other services, such as lighting, drainage, marking systems, and telecommunications). Furthermore, the current feasibility of applying LCA on roads is evaluated through a comprehensive review of available databases, methodological adaptations, software, and specialized tools.

To achieve this, the article is structured as follows: Section 2 describes the review methods; Section 3 presents the results, structured according to the scope of the research, including the foundations and fundamental principles, methodologies, standards, databases and tools, and case studies. In Section 4, results are discussed, identifying research effort and future work, and finally, Section 5 summarizes the main conclusions of the study.

2. Materials and Methods

The review method consisted of searching, analyzing, and discussing the fundamentals and principles of the life cycle assessment as applied to roads, available norms and standardization, resources, and development tools, including calculation tools, software, and databases, as well as case studies involving LCA in road projects. The primary sources of information used were the Web of Science (WOS) and Scopus databases; the keywords collected are shown in Table 1. The search strategy focused on titles, abstracts, conclusions, and keywords related to LCA and roads. Data collection, selection, analysis, and visualization were performed using 'Microsoft Excel ' and 'VOSviewer 1.6.19.'

Table 1. Keywords used in the search for resources.

KEY 1. **General Aspects**	**Frameworks and Methods:** Life-cycle assessment, sustainable development, road network sustainability, neutral roads, friendly roads, life cycle costs, infrastructure resource management	**Road categories:** Road, highway, motorway, street, transport project, suburban, non-metropolitan road, rural road, national road, local highway, country road, expressway, extra-urban, interstate
KEY 2. **Life Cycle Road Stages**	**Raw material** extraction, processing raw material, transformation, transport. **Construction:** earthworks (demolition, clearance, excavation, finishings, landscaping, transport of excavated material and imported soil and surplus soil, cutting, banking), drainage work (gutter, culvert, open channel, crossing drainpipe, vertical drainpipe); pavement work. **Use:** operation, maintenance, traffic monitoring, and control. **End of life:** repair, replacement, and rehabilitation.	
KEY 3. **Road elements**	Asphalt pavements, surface layer, antifrost heave layer, subbase layer, access road, footpath, marking signals, noise barriers, sewer systems, drainage systems, telecommunications, electricity, lighting systems, road safety, irrigation systems.	
KEY 4. **Impact Categories**	GHG emissions, global warming, human health, stratospheric ozone depletion, ionizing radiation, fine particulate matter formation, photochemical ozone formation, terrestrial acidification, freshwater and marine eutrophication, toxicity, water and land use, mineral resource and fossil resource scarcity, toxicity potentials, midpoint and endpoint categories.	
KEY 5. **Sustainable Strategies**	**Strategies:** Low impact construction, recycled materials, by-products, waste management, green pavements, wildlife crossings, permeable pavement, zero emission roads.	**Trends** Carbon-neutral road, autonomous vehicles, smart road technologies, Internet of Things, integration of renewable energy, adaptive traffic signals, smart transportation systems, low-emission roads, electrified road systems (eRoad systems)

Furthermore, Dimensions.ai software was used to retrieve additional data related to the terms 'Life Cycle Assessment' and 'Roads'. This initial search yielded 787 publications and 646 scientific articles published from 1994 to 2023. The publication dates for this initial analysis were not restricted to obtain a comprehensive historical perspective of the methodology's evolution. As Figure 1 illustrates, there has been a significant increase in research efforts in the field since 2014.

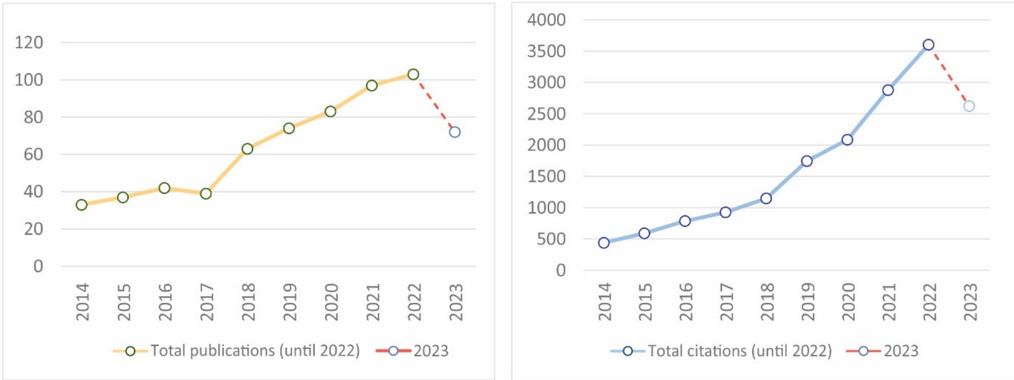

Figure 1. Number of publications (**left**) and citations (**right**) of 'LCA' and 'road'.

The contribution of publications to various research domains and Sustainable Development Goals (SDGs) was also analyzed. As shown in Figure 2 (left), the field of 'Engineering' has the highest number of LCA publications (533). Within this field, 'Civil Engineering' stands out with 326 publications, while the rest of the subareas (as 'Environmental Engineering', 'Materials Engineering', or 'Chemical Engineering') are less developed. When analyzing the alignment of each publication with the SDGs (Figure 2, right), most publications are associated with SDG 13 'Climate action', comprising 269 articles, followed by SDG 12 'Responsible Consumption and Production' with 219 articles, and SDG 7 'Affordable and clean energy' with 189 articles.

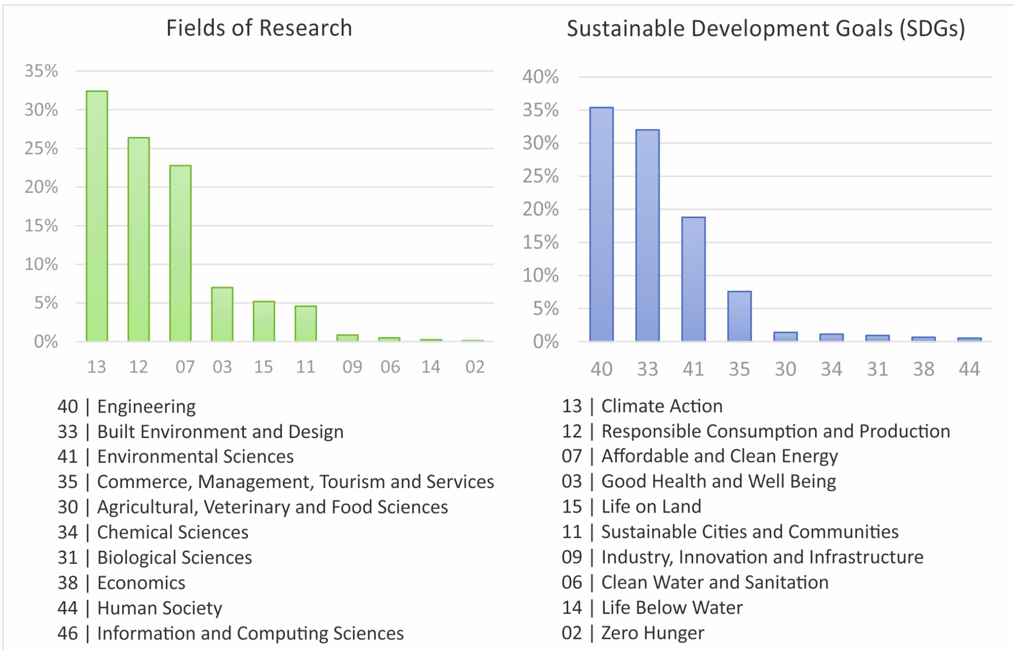

Figure 2. Number of publications about "LCA" and "road" classified according to SDGs and research field.

Of the total number of identified articles, an initial sample of 300 works was selected from the Web of Science (WOS) and Scopus databases. Of these, 150 were initially excluded, mainly because they did not align with the scope of this review. Subsequently, a comprehensive review of the sample was performed, categorizing the articles according to their relevance and contribution to LCA in road applications. The sample was classified into five categories according to its focus: (1) articles related to methodology (including publications with methodological developments aimed at facilitating the application of LCA to roads); (2) LCA tools and specialized LCA calculation software for roads; (3) case studies, further classified according to the scope of the life cycle: 3.1. The entire road; 3.2. Pavement; 3.3. Specific road systems, such as drainage systems, lighting systems, or transportation systems. Figure 3 illustrates this classification by typology and publication frequency over the years. The results indicate that 10% of the collected references belong to the category of "methodologies", 13% to LCA tools, and 71% to LCA applications.

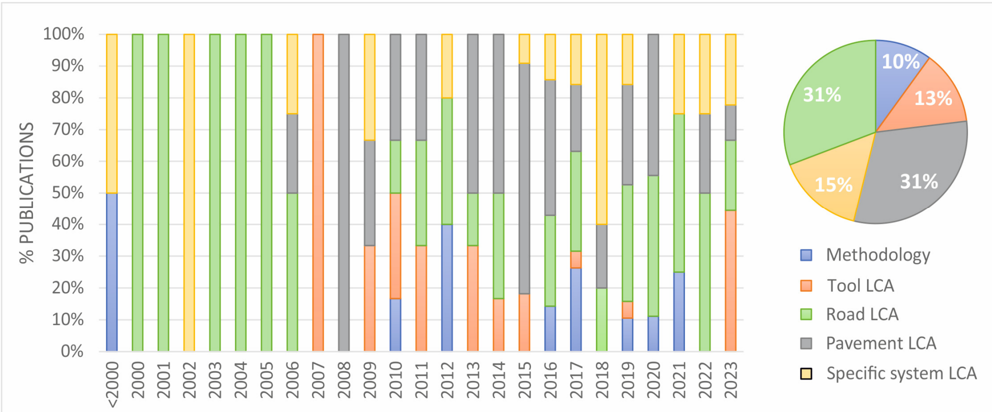

Figure 3. Publications according to distribution by year (**left**) and scope (**right**).

Table 2 presents a ranking of the most frequently published journals in the field of LCA applied to road infrastructure. *The Journal of Cleaner Production* leads with 87 publications, followed by *The International Journal of Life Cycle Assessment* with 69 articles. *Sustainability and Transportation Research* also stands out.

Table 2. Scientific journals published most frequently in the field of applied LCA in roads.

Position	Source Titles	Publications
1	*Journal of Cleaner Production*	13%
2	*The International Journal of Life Cycle Assessment*	11%
3	*Sustainability*	6%
4	*Transportation Research Part D Transport and Environment*	5%
5	*Resources Conservation and Recycling*	4%
6	*The Science of The Total Environment*	3%
7	*Journal of Industrial Ecology*	2%
8	*Materials*	1%
9	*Waste Management*	1%
10	*Applied Sciences*	1%

Finally, to understand the scientific progression in LCA, a coauthorship analysis was carried out using VOSviewer software. Figure 4 presents a visual map of the authors most frequently published and their affiliations. Joao Santos from the University of Twente (The Netherlands) is the most cited author, followed by Gerardo W. Flintsch from Virginia Tech (United States). Furthermore, the analysis identified three clusters of authors with high commonality, differentiated by various colors on the map.

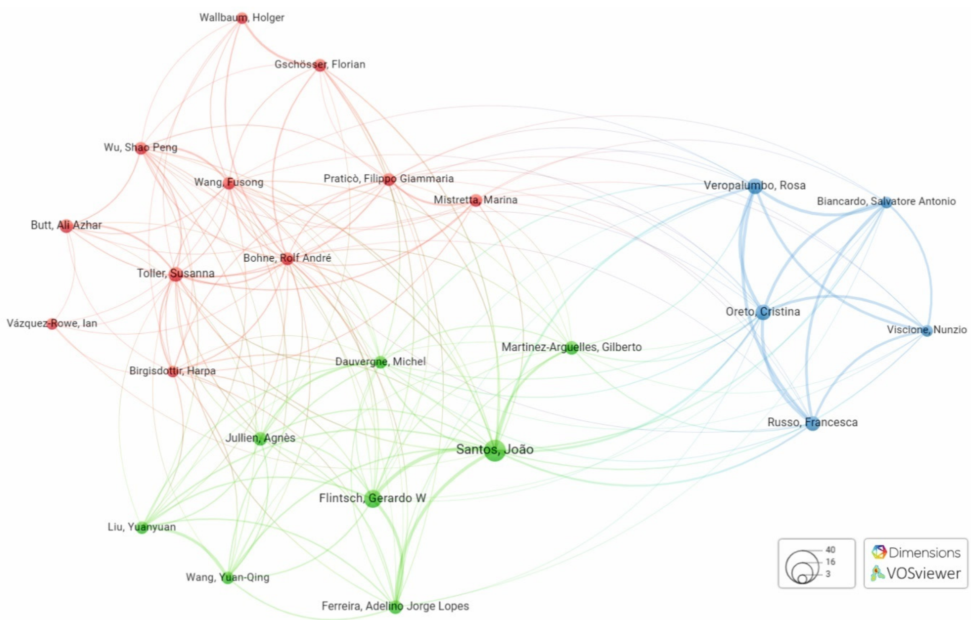

Figure 4. Co-authorship analysis in the field of LCA applies in roads.

3. Results: Life Cycle Assessment Applied to Roads

This section presents the results, which have been organized according to the objectives of the review: Section 3.1, evaluation of the LCA procedure applied to roads; Section 3.2, evaluation of ongoing research efforts in this domain within the scientific community; section; and Section 3.3, determining the availability of technical and digital resources for the practical use of LCA.

3.1. LCA Fundamentals for Road Lifecycle Analysis

Since early studies on environmental impact analysis focused on consumer products in the 1970s [33] and the subsequent evolution toward a life cycle-centered approach to building design, aimed at promoting the utilization of renewable resources [34], the interest in advancing knowledge, methodologies, and tools for environmental impact analysis remains relevant today. After a period where sustainable strategies were frequently employed as marketing tactics (greenwashing), often based on results lacking verifiability and rigor, the scientific community recognized the need to establish a consensus in the application and adoption of life cycle impact analysis techniques for products, processes, and services.

Beginning in the 1990s, a group of experts led by the Society of Environmental Toxicology and Chemistry (SETAC) published technical guides and best practices, culminating in 1993 with the establishment of a framework for the application of life cycle assessments [35]. Finally, in 1998, the International Organization for Standardization (ISO) harmonized the procedure within the ISO 14040 series of standards, incorporating a "methodological reference framework", as found in both ISO 14040 [18] and ISO 14044 [36]. Currently, LCA is a widely adopted methodology used to evaluate the environmental, economic, and social impact of any product, process, or service throughout its life cycle [18]. Although standards provide a structured approach to apply LCA in any sector, there is a growing trend of adapting these to specific industries. Over the past decade, there has been a concerted effort to develop specific standards aimed at customizing impact calculation models for each system-product and facilitating the application of the methodology. In the construction sector, this trend began in 2003 [37] and has continued through the establishment of various technical committees. Specifically, the International Organization for Standardization houses the ISO/TC 59 (Buildings and civil engineering works), and the European Committee for Standardization hosts the CEN/TC 350 (Sustainability of construction works). Their objectives focus on the development of standards to assess sustainability in construction, including the following most representative regulations [38–44].

Examining the standard LCA procedure and the environmental impact calculation model used, it becomes evident that it is a lengthy and complex process closely tied to a comprehensive study of the system-product under analysis. In particular, the ISO 14040 standards outline the four stages represented in Figure 5. In the initial phase, the goal and scope of the study, the reference unit (or functional unit), including system boundaries, and the level of detail, are established. The degree of detail chosen depends on the field and the intended purpose of the study. The second phase involves performing a life cycle inventory (LCI) analysis, which requires collecting input and output data related to the system under examination. Subsequently, this inventory is used in the third phase, the life cycle impact assessment (LCIA), with the primary goal of providing information to assess the results of the LCI and understand its environmental performance. Finally, the life cycle interpretation phase synthesizes and discusses the results of the LCI and LCIA to draw conclusions, make recommendations, and inform decision making according to the predefined goal and scope.

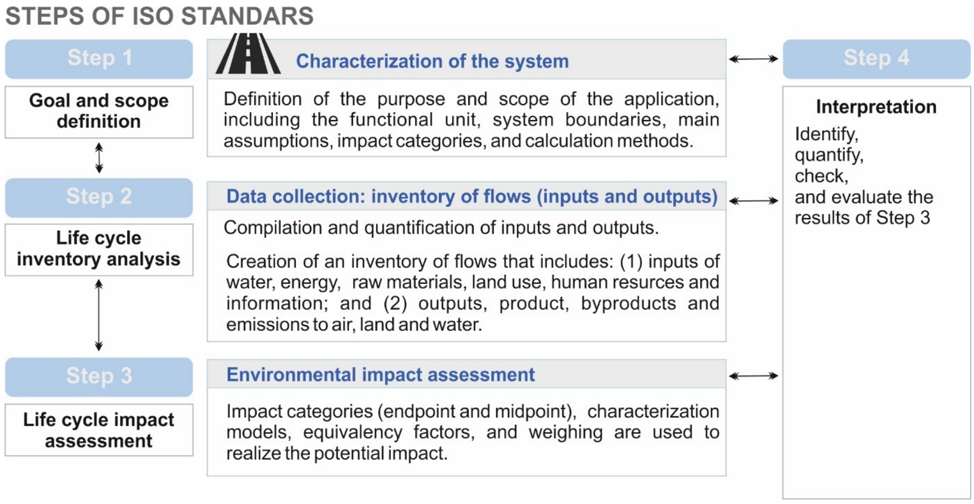

Figure 5. Stages of an LCA according to ISO 14040.

When this procedure is applied to a road, a significant level of complexity emerges due to the multidisciplinary nature of the life cycle stages and the unit processes associated with this type of infrastructure. Several disadvantages are specifically identified.

- The standards require that the road is defined as a "product system," which means that there is no single solution to define the functional unit and system boundaries. To date, no research has examined or provided the necessary recommendations for establishing these two aspects, which are essential to ensure the accuracy and comparability of the results among different models.
- Furthermore, the substantial volume of data required to create a comprehensive and representative life cycle inventory (LCI) of a road involves a significant investment in terms of time and cost. Currently, there are no guidelines for determining which data, processes, or environmental impacts are more representative or significant. There is currently no consensus on establishing common requirements to develop an LCI, LCIA, or implementing an LCA on roads.
- On the other hand, in LCA, the life cycle is modeled by disaggregating each stage of the system into a set of processes, categorized in Figure 6. To develop the LCI, it is necessary to quantify inputs (materials, energy, substances, equipment, etc.) and outputs (emissions into the atmosphere, hydrosphere, and lithosphere) to subsequently calculate the resulting environmental impact. The analyst must have a deep familiarity with the evaluated system, its functions, and the ability to subdivide it into unit processes.

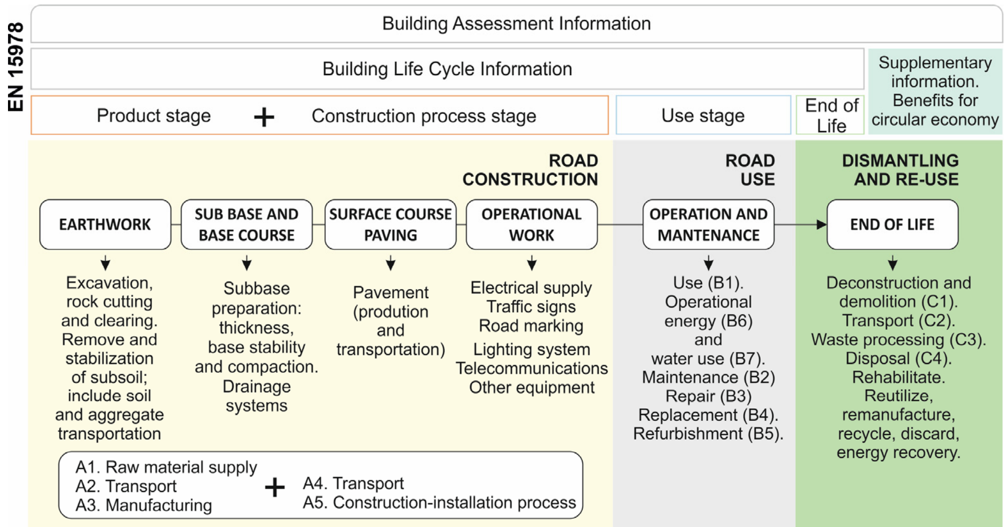

Figure 6. Key Processes in the life cycle of a road adapted to EN 15978.

- Finally, the structure of the results complicates the interpretation phase (step 4, Figure 5). This complexity arises from several factors: (1) a sequential arrangement (from emissions to midpoints and ending in endpoints) [45]; (2) the variety of indicators of environmental impact categories for midpoints (ranging from 7 to 30 indicators depending on the methodology) and endpoints (3 indicators); and (3) the level of calculation of the results, including classification, characterization, normalization, grouping, and weighting. This approach requires the analyst to acquire specialized knowledge in both the system product (in this case, roadways, transport infrastructure, and construction processes) and the analysis of environmental impact indicators.

3.2. Research Efforts Analysis

The scientific literature covers a variety of studies that develop LCA models for roads. As discussed in Section 2, the reviewed publications were classified into different groups: methodologies, tools, and study cases, including road LCA, pavement LCA, and specific system LCA. Within the study cases, the majority found in the literature include incomplete system boundaries, only considering the surface layer (asphalt and cement concrete) (31%), and only 31% of those analyzed consider the entire roadway. In addition, 15% analyze specific systems and services (electrical supply, lighting system, telecommunications, traffic signs, and others). Excluding those exclusively focused on pavement (as that topic has been the subject of study in other literature reviews), the rest of the studies were analyzed in detail, covering: (1) functional unit (Figure 7a); (2) system boundaries (Figure 7b); (3) scope of assessment (Figure 7c); and (4) integration of environmental and economic impact analysis (Figure 7d). The complete results can be found in external file (can request it from Correspondence author).

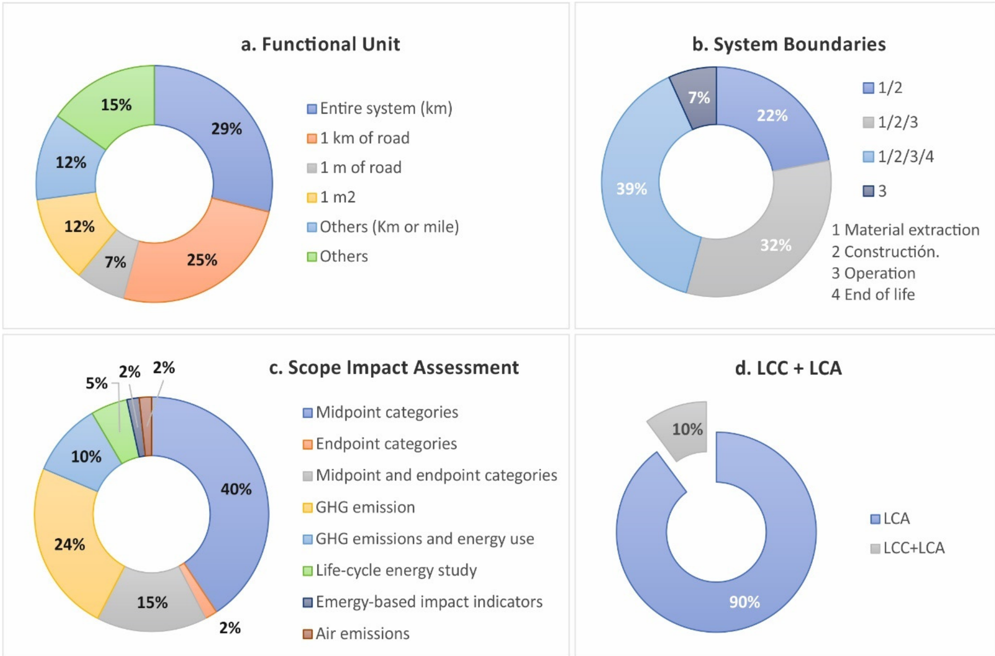

Figure 7. Characterization of results of the road LCA review.

During the definition of the goal and scope, one of the fundamental decisions involves determining the functional unit (FU). The FU is a quantified description of the performance of the product systems, used as a reference unit [46]. This is essential for modeling a product-system as it ensures representative and reality-aligned results and allows for comparative studies among systems. Figure 7a presents a classification of the types of unit selected in LCA models of roads, and from this classification and analysis, the following conclusions can be drawn:

- To properly define the FU, the following aspects must be considered: (1) the function or service provided; (2) the extent of the function or service; (3) the expected level of quality; and (4) the duration (useful life or lifespan) of the system [47].
- First, in terms of function or service provided, the most selected functional units in road LCA models are 1 km, a complete system (in km), or a combination of systems (km from several roads), 1 m, and 1 m^2. Other cases include the number of kilometers traveled, the annual transportation service offered, or cross-sectional areas.
- Regarding the extent of the function or service, most publications establish this to be coincident with a reference service life, which means the duration or lifetime of the system. This period varies between 10 and 100 years, with the range from 20 to 45 years being more prevalent. The lifespan of the system is related to its end of life. For a road, the end of life can be considered to be complete dismantling, although other authors consider it to coincide with a major rehabilitation or pavement upgrade. Furthermore, the lifetime is influenced by typology (highway, street, suburban, non-metropolitan road, etc.) and use (rural, local, or country road). Lifecycles tend to be shorter for systems with more intense service and surface wear due to traffic frequency (as in country, urban, or suburban roads), while they can be longer (as in rural roads). The location of the road in relation to climatic conditions also affects its lifespan; generally, harsher climatic conditions, such as winters with periodic freezing cycles, lead to more frequent maintenance and rehabilitation.
- Studies do not consider the expected level of quality.
- Finally, it should be noted that 75% of the studies develop comparative LCA models or establish some form of comparison between solutions, scenarios, or alternatives within road design. Some publications use FUs that are not suitable for this type of study; for example, considering “total road kilometers” to compare roads of different

dimensions or using cross-sectional areas, which vary depending on the route of the road due to terrain variability or the distribution of other components (such as width of lanes, services, or internal or external shoulders).

- This situation underscores the importance of examining the influence of FU on the reliability of environmental impact results in LCA applied to roads. It is essential to understand which FUs are most suitable based on the goal and scope, as well as to establish standardized guidelines with recommendations for their definition in these systems. Finally, the scientific community has a significant need to advance in performing sensitivity analyses of LCA results, taking into account FU variations, identifying sources of uncertainty related to their definition, and evaluating their impact on the LCI and LCIA phases.

Continuing the analysis of system boundaries, it was found that not all studies integrate the same stages. Figure 7b illustrates this variability by categorizing the boundaries into four stages: material extraction, construction, use, and end of life. The following conclusions can be drawn.

- Very few articles conduct a complete life cycle analysis of a road. The article by Stripple [48] is recognized as the first to apply LCA to a whole road. It still stands as the most comprehensive and closely approximates an LCA model based on ISO 14040.
- Most studies (93%) consider the stages of material extraction and construction-manufacturing within the system boundaries. Within these phases, 100% of the studies include the life cycle of the pavement, and partial analyses that exclude end-of-life (54%) are more common. This is due to the relative importance of the pavement compared to other elements in terms of environmental (and economic) impact. There is a greater variety of documentation and data available on pavement, and there is a preferred interest in the research line identified by the increasing number of researchers developing pavement LCA models in the last decade [5,49,50].
- Inclusion of raw material transportation, equipment, and other material resources throughout the life cycle of the road is infrequent. Additionally, in most studies, road configuration, components, and the design of other services (such as lighting, marking systems, and telecommunications, among others) are not considered.
- In the use phase, maintenance activities are typically limited to the pavement, excluding other elements and road systems, such as lighting, telecommunications, electricity, and marking systems. Most studies also omit traffic analysis, failing to account for the environmental impact of the main primary service or function of the product-system, including factors like fuel consumption, vehicle emissions, or pavement rolling resistance. Additionally, other frequently excluded aspects include the effects of land use and transformation, albedo assessment (solar radiation on pavement), light pollution, or biodiversity impact.
- The end-of-life phase of the road is excluded in 61% of the publications. It is important to note that studies that include it often address it in a limited way, compromising the accuracy and reliability of the results. This occurs for several reasons: (1) the lack of data availability; (2) the consideration of this phase as one of the least influential or relevant compared to the design and construction phases, where key decisions are made to reduce impact; or (3) planning road remodeling or service changes, eliminating the need for demolition.
- Although studies that analyze the entire road do not include all components and systems, there are other research efforts focused on specific aspects, components, or services that can complement the environmental impact analysis and provide a more comprehensive and detailed understanding of the environmental impacts associated with roads.
- This includes road components such as sidewalks [51], bridges [52,53], tunnels [54] or drainage system [55,56]; road systems and services, including marking systems [57,58], noise barriers [59,60], lighting systems [61–63], transportation and its influence on the use and operation phase [64–66]; the impact of incorporating new sustainable tech-

nologies to improve road environmental performance [67,68]; as well as comparative studies of emissions generated on roads compared to other transportation systems [69] or the type of transport carried out on roads compared to others, such as trains or airplanes [70].

Finally, the methodology to calculate the environmental impact of each LCA model was examined. The studies' scopes can be classified based on the impact indicators employed (Figure 7c): midpoint (41%), endpoint (2%), and combined (15%); individual categories are also used for analysis, such as GHG emissions (24%), energy consumption (5%), or combined GHG emissions and energy use (10%). Less common cases include the calculation of "air emissions" or the utilization of energy-based impact indicators. Various impact assessment methods are used for these calculations, with the most commonly used being CML, Eco-indicator, Recipe, or IPCC. Of all the studies analyzed, only 10% incorporate an integrated economic impact analysis through the life cycle costing methodology with environmental impact (Figure 7d). Many studies restrict their results to specific impact categories, with global warming being the most used indicator in the midpoint approach, and human health in the endpoint approach. Other categories frequently analyzed include human toxicity, acidification, eutrophication, and ozone layer depletion.

3.3. Availability of Technical Support and Digital Resources

To facilitate the creation of LCA models, a variety of resources have been developed since the 1990s, including software, databases, guidelines, recommendations, and methodological adaptations. The initial tools emerged in academic and university contexts, as the method was primarily intended for research purposes. Subsequently, there was a growing need to integrate technical and research professional competencies to facilitate the development of knowledge in environmental impact assessment within engineering contexts. Finally, due to the demand for commercial tools and the interest of the industry in their use, the market for professional software applicable to LCA has experienced significant growth in the last decade. There are various tools available that are suitable for any purpose and for any user, including researchers, consultants, technical designers, or sustainable project managers. They also support system analysis in any economic sector for product, process, or service analysis. Furthermore, they can be adapted to different scopes, encompassing environmental impact assessment, environmental management accounting, substance and material flow analysis, life cycle management, targeted information disclosure, certification, and eco-labeling. Table 3 provides a comparison of available professional tools, with a license cost ranging from €300–€15,000, depending on the duration (annual-indefinite), the type of software, and the completeness of the databases. Additionally, open-source software options are available, with costs linked solely to the acquisition of the corresponding database.

Among the tools listed in Table 3, SimaPro and GaBi have been available on the market for more than two decades and are the most widely used. Both have proprietary code, so they require a licensing investment. Another widely used commercial tool is Umberto, developed by Ifu Hamburg; it has a more complex and less intuitive interface than its competitors SimaPro and GaBi. In comparison, openLCA is an open-source tool that allows for the integration of both free and proprietary databases. This solution is attractive for any organization or user starting out in LCA. However, the user interface is less intuitive than SimaPro or GaBi, implying a steeper learning curve than other competing tools. Finally, it is worth noting that the One-click LCA tool, with less history but a growing trend of use, is integrable with BIM, Excel, and Revit (among others). Therefore, it is currently one of the best professional tools for use in collaborative work environments, which are becoming increasingly common in the construction sector. Although using a tool to perform LCA is essential today, the primary driver of the calculation model is the inventory database. Its quality and completeness are crucial to obtaining representative impact results. Consequently, over the last two decades, various databases have been developed, all of which are integrated into professional tools; some, such as GaBi, One-click LCA, or Open LCA, include their own databases. When analyzing the available databases two main groups can be identified: (1) generic or globalist groups primarily developed within academic and specialized company contexts, such as Ecoinvent, GaBi, SOCE, or ELCD; and (2) those specialized in a specific sector, product, or activity, such as Agri-footprint or Social Hotspots. The development of the latter is driven and incentivized by regulations, which require databases adapted to each economic practice. Generic databases include a large volume of data categorized into various areas (materials, energy, transport, transformations and production processes, waste management and treatment, etc.) suitable for integration into any analytical context. These are more complete in terms of elementary inventory flows. In comparison, specialized databases provide a higher level of detail in their unit processes, enabling the comparison of identical inputs from different manufacturers (e.g., raw materials). This potential allows for the assessment of industrial variability, compared to generics, which offer approximate results by geographical region. Tables 4 and 5 show a comparative analysis of the most representative and widely used open-source and private databases currently available.

Table 3. Comparison of professional and high-impact commercial tools.

Tool	Description
SIMAPRO	Leader in industry, research institutes, and consultants in more than 80 countries. It offers features and analysis packages for experts in the field.
Gabi	Leader in industry, research institutes, and consultants in more than 80 countries. It has its own database and provides high flexibility in model creation.
UMBERTO	Ranked third in industry, consulting, research, and development sectors, this software has been used professionally for more than 25 years.
Air.e LCA	Developed in 2009, it includes all the necessary functions in an LCA tool that are simpler and more flexible than others on the market.
Open LCA	The only open-source tool at a professional level for ecological, social and economic LCA, in addition to carbon and water footprints, ecological design, environmental product declarations, and LCC.
REGIS	Focused on organizations and specialized in implementing LCA software in companies to analyze and control their corporate EcoPerformance (Company-LCA, with regionalized LCI/LCIA).
One-Click LCA	Collaborative database with more than 90,000 data points. The most specialized in construction and building. Integration with Excel, Revit, IFC, IESVE, energy models (gbXML), and other platforms.
eBalance	Developed by IKE Environmental Technology, it uses high-quality Chinese and global databases. It is the preferred choice for conducting LCAs of products manufactured in China.
EIME	Industry-oriented, its user-friendly and ergonomic interface enables all users, including nonexperts, to conduct in-depth analyses.

Table 4. Analysis of Open-Source Databases (DB).

Database	Main Features
Environmental Footprints (EF)	Included in the PEF (Product Environmental Footprint) project of the European Commission, which aims to establish a "Single Market for Green Products," this tool focuses on the quantitative assessment of the environmental impacts of products and the analysis of environmental footprints in organizations.
IMPACT World+	Uncertainty analysis from spatial-geographical variability. Differentiation of impact categories at the regional level based on location, both short- and long-term damage (up to 100 years after emissions). Includes specific characterization factors for various countries, global or continental coverage, including Latin America.
OZLCI2019	Covers Australasia's regional supply, including imports; it can be integrated with other free DB.
Exiobase	Multiregional; includes use-supply and input/output data. Harmonized and detailed supply-demand DB for a large number of countries, estimating emissions and resource extractions by industry. It can be used for the analysis of the environmental impacts associated with the final consumption of product groups.
Arvi	For production chains for wood and polymer composites. It includes a wide range of global and local parameters.

Table 4. *Cont.*

Database	Main Features
Agribalyse	Focused on the agricultural and food sector. It includes ICV for 2500 agricultural and food products produced and/or consumed in France, combining a production-based approach and a consumption-based approach.
Needs	New Energy Externalities Developments for Sustainability, for future electricity supply in Europe. It contains industrial inventory data on future transportation, electricity supply, and materials services.
ELCD (European reference LC DB)	It includes 330 inventory datasets from leading European business associations (chemical, metallurgical, energy production, transport, and end-of-life processes).
Bioenergidat	Processes for bioenergy supply chains of German origin.

Table 5. Analysis of private databases (DB).

Database	Main Features
Ecoinvent	Leader in ICV for the industry. High volume of data from unit processes and products from agriculture, building materials, chemicals, electricity, metals, transportation, and waste treatment, among others.
UVEK LCI data * Requires Ecoinvent	Based on Ecoinvent v2.2, it updates some key energy areas, such as crude oil supply, natural gas, nuclear fuel and electricity, transport and disposal services, and the forestry and wood industry.
The Evah Pigments Database	Specialized in pigments; it contains 55 pigments, including 31 inorganics of 16 different colors from eight regions and 24 organics of 10 different shades from five regions.
LCA Commons	9200 U.S. datasets of unit process models and product systems related to agricultural production.
IDEA v2	Hybrid that presents statistical and process-based data. It comprehensively covers almost all economic activities in Japan and contains about 3800 processes according to Japan's Standard Product Classification.
Agri-footprint	From food, it contains data on agricultural products (feed, food, and biomass).
SOCA	Extension for Ecoinvent, aimed at the social impacts of products.
Eugeos'15804-IA *	The Ecoinvent complement focused on the requirements of the EN 15804 standard for EPDs compatible with ISO14025 and registered on the ECO platform.
Estimol * requires Umberto	It contains 14,000 chemical compounds and their values of global warming potential (GWP), accumulated energy demand (CED), and endpoint.
PSILCA	Complete generic inventory information for nearly 15,000 industrial and commodity sectors for social impacts of products and hotspots.
ESU world food	Focused on the global food sector, it includes more than 2100 processes related to agriculture, food processing, and consumption activities.
Social Hotspots	For social LCA and human rights, it enables global supply chain modeling in more than 140 countries and 57 sector-specific indicator risks.
ProBas *	Of German origin, it includes unit and aggregate processes for energy, materials and products, transport services, and waste.
Okobaudat *	Building Materials Database (German Federal Ministry of Transport, Building and Urban Development)
IBO *	Integrated in the German tool ECO2SOFT, it is intended to calculate the impact on buildings (Austrian Institute for Healthy and Ecological Building GmbH)
SYNERGIA *	Database integrated into the SYNERGIA carbon footprint tool of the Environmental Institute of Finland

* Specialized road databases.

Ecoinvent stands out as the most renowned due to the quality and completeness of its data. Although it is not explicitly specialized in roads, it does include modules and data sets relevant to this context. The existing specialized databases are identified in Table 5. ATHENA is a notable example in the construction sector. However, it is currently not commercially available, and its scope is limited to scenarios in the United States and Canada [71,72]. The cost of a license varies depending on the data completeness and scope, ranging from 100 EUR to 10,000 EUR, with some offering open access. The availability of both generic and specific databases is a key indicator of the quality of a software tool. It contributes to better results in the LCA process and impact calculation. As illustrated in Table 6, high-end professional tools commonly incorporate a variety of databases; for example, GaBi and Open LCA have developed their own databases, and ONE CLICK LCA has a collaborative open database that integrates data from most EPD (Environmental Product Declarations) platforms and provides manufacturer-specific data.

Table 6. Integration of LCA Databases in Commercial Tools.

Data Base	SimaPro	GaBi	Umberto	One Click LCA	Open LCA	Aire LCA	REGIS	EIME
Own		x		x	x	x		
AGRIBALYSE	x				x			
Agri-footprint	x				x			
DATASMART LCI package	x							
Ecoinvent	x	x	x	x	x	x	x	x
ELCD	x				x	x		
Environmental Footprint database	x	x						
EstiMol			x					
ESU	x				x			
EuGeos' 15804-IA					x			
European and Danish Input/output DB	x							
EXIOBASE	x				x			
GaBi database		x	x			x		
IDEA Japanese Inventory database	x				x			
IMPACT World+					x			
Industry data library	x							
KBOB—IPB (UVEK LCI Data)					x			
LCA Commons					x			
Okobaudat					x			
PSILCA					x			
Social hotspots database	x							
Swiss Input/output database	x							
The Evah pigments database					x			
US Life Cycle Inventory database	x	x				x		
WEEE LCI database	x							
Environmental Footprint database (UE)					x			
Others				x	x		x	x

All high-end professional tools and integrated databases enable a complete analysis of any system and provide highly precise calculation results. However, they have the drawback of requiring substantial investment in terms of both cost and time. In addition, LCA expertise and a deep understanding of the specific system under evaluation are essential to create LCA models. However, in the construction and road sector, the lack of specialized databases can compromise the quality of the results. Over the past decade, the scientific community, certain public administrations (such as the Netherlands and France), and private organizations involved in the construction and transportation infrastructure sector have developed LCA frameworks and tools specialized in the industry to address this challenge. Their main objective is to simplify study design and provide more accessible and cost-effective tools for non-expert LCA users. This is achieved through streamlined analysis methods, the inventory process, and specialized database information. In the scientific literature, specialized methodologies for road LCA are also proposed. There are models that aim to improve the environmental performance of roads during the design phase [73–75], select optimal materials to minimize environmental impact [76–78], or simplify the development of LCA models [79–82]. Innovative research is also being conducted to improve LCA processes using new technologies, such as optimizing life cycle inventory generation through geoinformation systems or spatial geological data [83,84] and digitally integrating LCA into building information models (BIM) [85]. Table 7 provides a comparative analysis of the specialized LCA tools applied to roads. It can be concluded that most of these focus on analyzing climate change, carbon footprint, and GHG emissions, while options with a broader range of impact indicators are limited in number.

Table 7. Comparative analysis of non-commercial tools specialized in road LCA.

Tool/Scope	Scope of Analysis
ATHENA road [86]	Free ISO 14040-based LCA software for the design and construction of US and Canadian roads: material extraction, road construction and maintenance, and waste management.
Carbon gauge tool/PEET [87]	Use in the early stages of a land transport infrastructure project (state highways, local roads, and rail).Scope: GHG assessment; construction, operations and maintenance; vehicle use
CFET road [88]	Road construction projects and other components of transport infrastructure in the construction stages, including reforestation offsets. Scope: Carbon footprint only and GHG emissions analysis
CHANGER/road [89]	Measurement and benchmarking of the carbon footprint of road construction worldwide. Scope: Calculator for harmonized assessment and normalization of GHG emissions for roads
CMS RIPT/road [90]	Road infrastructure projects, which provides a transparent mechanism to report CO_2 emissions at the construction stage. Scope: Only carbon footprint and GHG emissions analysis. Linked to a pilot project "CMS"
CO2NSTRUCT/road [91]	Information management system and calculation of impact related to GHG emissions. Scope: Comparisons between different technical transport infrastructure solutions
COPERT 4 [92]	Air pollutant and GHG emissions from road transport. Scope: applicable to all relevant research, scientific and academic applications.
DuboCalc/construction and infrastructures [93]	Environmental costs (EUR) of the environmental effects of material and energy from cradle to grave with the Environmental Cost Indicator (MKI). Mandatory use in the Netherlands in public procurement processes. Language: Dutch. Based on ISO 14040 and Environmental Assessment Method Buildings and Construction. Excel tool
e-CALC/Underground processes [94]	Underground construction procedures and different trenchless technologies in infrastructures. Compare construction methods and calculates the emissions generated. Scope: Carbon footprint. For underground equipment and processes.
ECORCE-M/roads [95]	Midpoint indicators by comparing different technical solutions offered by French companies during public procurement calls. Language: French. It uses LCI data collected from the scientific literature. Origin of the data is unknown
Greenroads/road [96]	Environmental, social and economic performance with expert third-party review. It is based on the "Greenroads Rating System" impact analysis weighting process. Weighted data (ISO 14040). Certification dependent on Greenroads®
LICCER/road [97]	Life cycle energy and GHG emissions of road infrastructure. Scope: Energy and GHG
PaLATE /Pavement [98]	Environmental and economic effects. Can be integrated into Greenroads Rating System. Scope: Only for pavement impact analysis. Excel tool
PE-2/road [99]	Estimates the carbon footprint of typical construction items in road reconstruction and rehabilitation projects. Scope: Only carbon footprint and GHG emissions analysis.
RoadCO_2/road [100]	Road projects in the preconstruction, construction, operation, maintenance, and rehabilitation phases of a project. It uses IPCC emission factors. Scope: Only carbon footprint and GHG emissions analysis.
ROAD-RES/road [101]	Life cycle of road transport infrastructures, useful for comparing relative impact contributions in different technical solutions. Scope: Only carbon footprint and GHG emissions analysis.
UK asphalt pavement LCA model [102]	Probabilistic ACL using the Monte Carlo method; uncertainty analysis of ICV of road pavements. Scope: airport pavement. Impact categories: primary energy consumption and GHG from material production and pavement construction
VTTI/UC/pavement [103]	Extraction and production of materials, construction, maintenance and rehabilitation, transportation of materials, traffic management, use, and end-of-life of a road pavement. Scope: Pavement. US data source

4. Discussion

In an increasingly competitive market, road consulting firms face growing administrative and social demands in terms of sustainability. This calls for the adoption of innovative approaches, including the integration of technical and environmental analysis from the early stages of the project, with the aim of reinforcing both environmental and social protection. As a fundamental principle [104], the implementation of more environmentally friendly solutions is only possible from the initial planning and design stages of the road, considering all stages of its life cycle. Considering environmental impacts at an early stage of the project leads to greater eco-efficiency [105], and the results are eco-effective [106]. This working approach requires the use of both predictive and impact assessment tools based on verifiable and accurate information to facilitate alternative comparisons and the selection of the optimal solution. In this context, life cycle assessment is one of the most used techniques. However, when applied to civil engineering, it presents certain limitations that require significant expansion and improvement efforts for road LCA models. This situation arises from various factors, including: (1) challenges in selecting the functional unit, (2) the use of diverse methods to assess environmental impact, (3) the combination of databases, information from the scientific literature, and/or real project data for the development of the life cycle inventory (LCI), and (4) defining system boundaries. The factors mentioned above frequently lead to analyses that lack comparability and reproducibility. To date, no research has been conducted to analyze or provide the required recommendations for establishing these aspects, which are essential for ensuring accuracy and comparability of the results across different models. Frequently, data extracted from existing scientific literature, either in its entirety or partially, are utilized, leading to the spread of errors from one study to another. Similarly, it is essential to expand the scope of studies to include additional impact categories, rather than a limited analysis to climate change, human health, or GHG emissions. It should be noted that, currently, both databases and software make it relatively easy to incorporate various impact categories that are relevant to suggest sustainable solutions in the context of a road, yet their utilization remains limited. All these constraints contribute to the application of LCA, occurring primarily in the later stages of road construction projects.

To address these challenges, current research efforts should focus on improving LCA models, primarily by refining their procedure. First, it is essential to examine the selection of the functional unit (FU) and its influence on the reliability of environmental impact results. Understanding the most suitable types of functional units and establishing guidelines and recommendations for their definition in such systems are necessary. It should be noted that the primary challenge in developing comprehensive and comparative LCA models for roads lies in defining the functional unit. This definition must meet several criteria: (1) The FU must be correlated with the configuration of the road, including the number of lanes, internal and external shoulders, footways, or non-motorized lanes; (2) The FU must account for variations in road dimensions based on its alignment in the terrain; (3) The FU must encompass not only the road as a cross-sectional area on the terrain, but also its constituent components; and (4) The FU should reflect the variety functional configurations of the road, based on terrain variations and the different services provided along its route, including lighting systems, telecommunications, or electrification, among others. This definition of FU is fundamental to ensuring that road LCA models are accurate, useful, and comparable, generating a comprehensive assessment of environmental impacts.

Second, the procedure also requires the creation of an inventory of inputs (materials, energy, equipment, water, and other resources) and outputs (substances and waste generated in each unit process and task) in its second stage. Subsequently, this information is used to calculate environmental impact categories. Currently, the quality of LCA results is compromised by several factors, including the scarcity of specialized databases, the timeliness and origin of data (regional/local), and the precision of inventory data. These issues impact the precision and validity of the studies. The available databases also have certain scope limitations. Few of them collect specific data on raw materials, equipment, unit processes, emissions, or waste needed to perform a complete life cycle inventory for a road. When such data sources do exist, they often require a significant investment of effort and time. Furthermore, these databases are typically developed for specific regions, with datasets commonly contextualized in European or American environments. When used in

LCA models for regions other than the one where the data originated, it can lead to errors and compromise the reliability of the results. Furthermore, LCI is a process that requires a comprehensive and systematic data collection, currently performed manually by an LCA expert familiar with the system under analysis. This is why software tools are essential when applying LCA to large systems, such as roads. However, available tools that provide results with lower uncertainty often come at a very high cost. In contrast, specialized tools have been mostly developed in academic and research settings and currently lack commercial applications. Although most of them are open source, user-friendly, and equipped with an intuitive user interface, they frequently have limited scope to define the boundaries of the system. They typically exclude certain stages of the life cycle or reduce impact categories, with the most developed focused primarily on analyzing the carbon footprint, climate change, and GHG emissions. The findings of the comparative analysis of available resources identify one of the future challenges for road LCA: improving specialized methods and tools, especially in terms of their configuration and completeness for inventory (stage 2) and environmental impact characterization (stage 3). In addition, road construction requires significant amounts of resources. Throughout the construction process, the use of virgin raw materials and the extraction of natural aggregates still prevail, leading to alterations in the landscape and disruptions in ecosystems. Adopting a life-cycle approach to mitigate environmental impacts and achieve a balance between the economic interests of the transport sector and environmental constraints requires an in-depth analysis. This evaluation should encompass traditional life cycle impact assessments using midpoint and endpoint indicators, with other specialized metrics related to material footprint [107,108]. These metrics provide a comprehensive evaluation of the life cycle of roads, ensuring a more thorough understanding of their environmental footprint. Furthermore, it is essential to progress toward harmonized certification systems for cost-effective, safer, and greener road infrastructures [109].

Finally, there is a growing need to develop parametric or algorithmic design tools that enable the utilization of LCA models in the initial phases of the project. These resources can streamline decision-making, facilitating the integration of economic and environmental impact analyses, which is a critical step in identifying more sustainable road solutions. The integration of these automated tools with the latest advancements in Industry 4.0 has the potential to significantly improve the development of road LCA models. By incorporating digital resources that combine sensors and control systems to monitor data collection throughout various life cycle phases, the life cycle inventory analysis (LCIA) is accelerated and made more dynamic [110]. This is a critical challenge for scientific community because this transformation can turn traditional LCA processes into an automated environmental assessment framework, often referred to as Dynamic LCA, adapting the approach to environmental analysis towards digitalization.

5. Conclusions

The multidisciplinary, complex, and interconnected stages of a road's life cycle, combined with the extensive inventory, scarcity of specialized data, methods, and tools, as well as the substantial investment of time and financial resources required for their execution, all contribute to the complexity involved in conducting LCA. Furthermore, the lack of specialized databases requires that compilation of inventories using data inputs that may be similar but originate from different locations, or, in some cases, even demand their exclusion from the system boundaries. This situation can lead to biased interpretations of the results and a reduction in the quality of the study. Lastly, there is a scarcity of open-source tools; standards, software, and databases come at an excessively high cost, not to mention that the procedure and the use of these resources must be conducted by an environmental analysis expert. Due to these challenges, the adoption of LCA in the road construction sector is still in its early stages. This situation underscores the need for new impact analysis tools that incorporate a versatile methodology, with specific characteristics of such an infrastructure, and that facilitate the application of the LCA procedure outlined in ISO 14040 and ISO 14044 standards, particularly for small and medium enterprises in the sector. These tools will aid in cost reduction and reduce the reliance on highly qualified environmental analysis experts, ultimately improving the cost effectiveness of impact analysis in such projects and promoting the development of more environmentally sustainable roads. Furthermore, it is crucial to continue advancing toward harmonized certification systems for cost-effective, safer, and greener road infrastructures. Enhancing evaluation metrics by combining traditional indicators like midpoint and endpoint with other specialized metrics related to the road life cycle is essential. These two trends can provide a comprehensive evaluation of roads' life cycle, ensuring a more thorough understanding of their environmental footprint. Finally, tools with greater capacity are required, allowing for the integration of parametric or algorithmic design and assessment resources, supported by digital tools to monitor data collection in life cycle inventory analysis with a dynamic process. These challenges are critical for the scientific community, as their scope will enable the transformation of LCA processes into an automated environmental assessment framework. This will facilitate the development of much more precise LCA models, with a streamlined process and significantly reduced time and cost investment compared to the traditional methods currently in use.

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