sustainability

Review

Life Cycle Assessment of Road Pavements That Incorporate Waste Reuse: A Systematic Review and Guidelines Proposal

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Abstract: Life cycle assessment (LCA) is a methodology that has been widely used to evaluate the environmental impact of products and processes throughout entire life cycles. In this context, the reuse of waste in paved road construction is a practice that has received increasing attention as a sustainable alternative to solid waste disposal. This article presents a systematic review of existing studies on the LCA of paved roads that incorporate waste reuse and proposes a guideline for LCA in this context. Several criteria were analyzed in the articles, and the results showed that only 5% of the articles followed all the recommendations set out in ISO 14040. The proposed guideline aims to provide guidance for future research and includes recommendations for each of the steps involved in LCA, from defining the objectives and scope of the study to interpreting the results.

Keywords: life cycle assessment; pavement; waste reuse; road; sustainable materials; highway; recycling; industrial byproduct; environmental impact; solid waste

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1. Introduction

The construction industry, one of multiple industries that has substantial impacts on the environment, is characterized by high energy consumption, the extraction of almost half of the world's natural resources, significant greenhouse gas emissions, and the generation of more than half of Brazil's solid waste [1–4]. For example, the disposal of waste resulting from construction and demolition constitutes a significant portion of solid waste, surpassing the amount generated by municipal activities by roughly twofold. Notably, the majority, more than 90%, of this construction and demolition (C&D) waste arises from demolition activities, while construction activities contribute less than 10% to the overall C&D waste [5]. Demolition work, although energy-intensive, plays a crucial role in the civil engineering sector and holds promise within the European circular economy framework [6]. In view of this, engineering researchers have dedicated their efforts to reducing these impacts and further promoting the circular economy. Among the strategies to increase resource efficiency in civil construction is the reuse of solid waste in the construction of paved roads [7].

According to Bernucci et al. [8], a paved road is a structure comprising multiple layers of predefined heights and built on a flat surface, whose purpose is to resist loads from vehicle traffic and climatic conditions, providing users with improved driving conditions, comfort, and safety. The construction of paved roads involves the use of various raw materials that cause a variety of environmental impacts when extracted from the environment. One of the ways to account for environmental impacts is through tools such as life cycle assessment (LCA).

LCA is a methodology that enables the qualitative and quantitative assessment of possible environmental impacts and resource consumption throughout a product's life cycle.

In other words, it considers all the effects that the product has, from the extraction of raw materials to the stages of production, use, disposal, and recycling. An LCA study consists of four stages: definition of objective and scope, inventory analysis, impact assessment, and interpretation [9]. The description of the LCA methodology is based on the requirements of the ISO 14040 [9] and ISO 14044 [10] international standards and is one of the most widely used and detailed environmental impact assessment methods in recent literature compared to other environmental assessment tools.

In recent years, researchers have investigated the replacement of raw materials with sustainable materials in road construction to mitigate environmental impacts. More recent studies have employed the LCA approach so that not only the technical feasibility of the input but also the environmental performance throughout the entire life cycle of the material's application is assessed [11,12].

Among the waste materials used as substitutes are reclaimed asphalt pavement (RAP) [13], tire rubber [14], construction and demolition [15], glass [16], slag [17], fly ash [18], plastics [19], fibers [20], bio-oil [21], roof tiles [22] and polymers [23]. These materials have been applied to the different layers of the paved road, from the asphalt coating in the top layer to the lower layers, such as the base, subbase, and embankment.

Some authors have reviewed the literature on the application of waste materials in asphalt roads, also addressing the issue of LCA, as is the case with the work by Bamigboye et al. [24]. Other authors have focused on studying the application of LCA to paved roads, with the aim of analyzing the phases of the methodology that have the greatest environmental and economic impact, as shown in the article by Alaloul et al. [25]. However, most reviews mentioned research in the literature and do not achieve more in-depth analyses of LCA application [26–29]. Therefore, there is a shortage of reviews that address the development of each stage of the methodology. In addition, there is disagreement among the authors; furthermore, no specific document guides the application of LCA to paved roads, apart from the ISO standard itself.

This article therefore presents a systematic review of the application of LCA to paved roads that integrate industrial waste and byproducts and a proposal for guidelines for future work. Statistical data from the studies found are presented, as is a critical analysis of each stage of the LCA. The findings resulting from this literature review aim to provide statistical data on LCA applications of recycled materials in paved road construction and to identify gaps in the body of work to date to suggest future research directions. At the end of the results, a guideline of good practices is presented so that LCA research is more assertive from the point of view of practical and academic application.

2. Methodology

The state-of-the-art ProKnow-C method was used. This method, also known as the knowledge development process and the constructivist method, was developed by the MCDA Laboratory at the Federal University of Santa Catarina and consists of four phases: selection of the bibliographic portfolio, bibliometric analysis, systemic analysis, and identification of gaps in the literature [30].

2.1. Selection of Bibliographic Portfolios

In the first stage, criteria were established for selecting the documents. Initially, we investigated which databases had the largest number of papers in the defined research area. The databases correlated with the journals that publish the most on the subject were identified; the ones selected were Science Direct, Scopus, and Web of Science.

The keywords chosen were those typically used by authors in the same field of research. A search was carried out using the combination of the words "Life Cycle Assessment", "Pavement", and "Recycled", which resulted in the largest number of relevant materials. To expand the search, the word "Recycled" was replaced by "Solid Waste" and "Reuse", resulting in three searches in three different databases.

It was decided that all the articles should be in English and published between 2013 and 2023 to select documents with current information. Regarding the quality of the journals, only those classified as quartile Q1 or Q2 in the Scientific Journal Rankings were considered.

2.2. Bibliometric Analysis

The titles of the papers were evaluated, and the number of citations of each article was checked. Only articles with 10 citations or more were analyzed, except for articles published during the last two years due to their short publication time.

Next, the abstracts of the selected articles were read, and those that mentioned only the LCA methodology without addressing its application were disregarded. Articles that addressed LCA in paved roads with a focus on sustainability but without the application of any recycled material were also excluded. At the end of the selection, 98 documents were selected and analyzed. Figure 1 graphically shows all the stages of the method applied in the research.

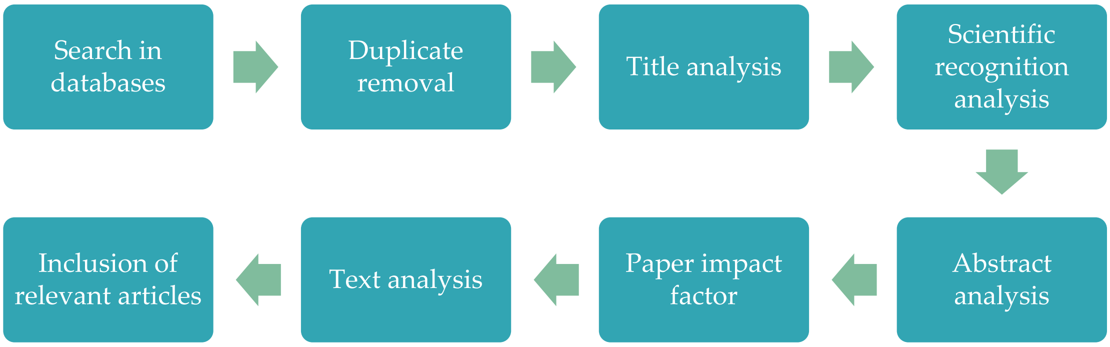

Figure 1. Stages in the application of the ProKnow-C method.

For bibliometric analysis, some data were compared, such as the year of publication, the journal in which it was published, the number of citations, and the country and institution of the first author.

2.3. Systematic Analysis

During the systematic analysis of the articles, a check was performed as to how the LCA methodology was applied. The ISO standard establishes the requirements and guidelines for LCA, covering all the methodological phases. As mentioned by Rebello et al. [31], although it is desirable for authors to follow the ISO guidelines, there are still no specific standards for each area and application, thus allowing authors to adjust to complete their particular studies. However, when details about the application of LCA are not provided, inconsistencies may be present that make it difficult to verify their veracity and impossible to create comparisons with other methodologies. An example of this is the lack of a clear definition of the objectives and scope of the LCA applied, which hinders an understanding of the purposes of the study and the limitations of the research. This lack of standardization prevents the replicability of studies.

According to ISO 14040, the LCA method is a systemic approach with four main phases: (1) definition of objective and scope; (2) inventory analysis; (3) impact assessment; and (4) interpretation of results [9]. Therefore, each article read was analyzed according to different criteria for each of the LCA phases.

The first criterion analyzed in the articles was the definition of the scope of the research. The definition of the objective and scope should be coherent, clarifying that the boundaries of the system, the period of analysis, and the functional units (FUs) have been determined. Checks were performed regarding a clear statement of the scope and the objective of the research. Regarding the boundaries of the system, the stages covered in the work, including the extraction of raw materials, manufacturing, construction, operation/maintenance, and demolition, were also accounted for. Finally, consideration was given to whether the FU was mentioned and whether the criteria for making this choice were provided; these factors enable comparisons of the results with other works.

The second criterion was related to the inventory phase of the life cycle. Factors considered included the use of primary data, i.e., information specific to the production processes of the product or service, or secondary data, which are general data or represent product averages. Some studies used both types of data, such as the study of Yang et al. [22]. The quality of these data was also considered by determining whether they were taken from practical applications, literature, or databases. In this stage, the software used was also analyzed regarding the use of any international databases, in which inventory data from various production processes specific to a country of origin are stored.

The third criterion checked was the analysis of the life cycle impact methodology. At this stage of the LCA, the data are categorized into specific impacts according to a specific methodology, which may include a single category (single category) or many categories (multicategory). The most widely used are multicategory methods, which can be problem-oriented (midpoint) or damage-oriented (endpoint). These methods are found in the various databases on the market and in software designed to interpret the results. Several different types are being used worldwide, such as Impact 2002+, created in Switzerland; ReCiPe, created in the Netherlands; and TRACI, created in the United States. Therefore, there is no single method for this stage.

We then determined whether any of the methodologies in the literature were applied in actual studies and whether these studies used the midpoint or endpoint approach, which indicates the categories evaluated. The allocation strategy for the waste-related impacts studied was verified, with three allocation options: (1) cutoff, in which all the impacts of producing that waste are disregarded; (2) extraction of the raw material from the waste; or (3) the 50/50 method, proposed by Martin et al. [32], in which an intermediate approach is considered, dividing the environmental impacts of the byproduct with the product but accounting for the mass balance.

Finally, the proposed guideline was developed based on the shortcomings identified in the application of LCA by analyzing the application of the regulatory requirements in each stage. In addition, good practices are recommended based on references widely cited in the literature and the choices adopted by the majority of authors.

3. Results and Discussion

3.1. Selection of Documents

By choosing the keywords and cross-referencing them with the chosen databases, approximately 428 articles were obtained: 170 from Web of Science, 156 from Scopus, and 102 from ScienceDirect. Clearly, the databases have a significant number of articles, and more than one must be searched to obtain a greater number of papers. The keywords that obtained the most results were the combinations of the two fixed words “life cycle assessment” and “pavement” with the word “recycled”, obtaining 85% of the results. This shows that the words “solid waste” and “reuse” are not the most used on the subject and could be disregarded. After excluding duplicates through the Mendeley reference manager, 336 articles were obtained, which shows that many articles are present in more than one database.

At the end of the steps, 98 articles were obtained, of which 9 were reviews and 89 were LCA applications. Notably, many reviews cited previous work but did not categorize the results of these studies for comparison. These are works based on citations, without a conclusive analysis. Figure 2 shows the number of articles in each phase of the ProKnow-C review method.

3.2. Bibliometric Analysis

Of the 98 articles read, 68.36% were written in the last 5 years, which shows that the topic of sustainability in pavement has been increasing over time. There are fewer articles in 2023 than in 2022, possibly because the survey did not consider the whole of 2023 (only the first half).

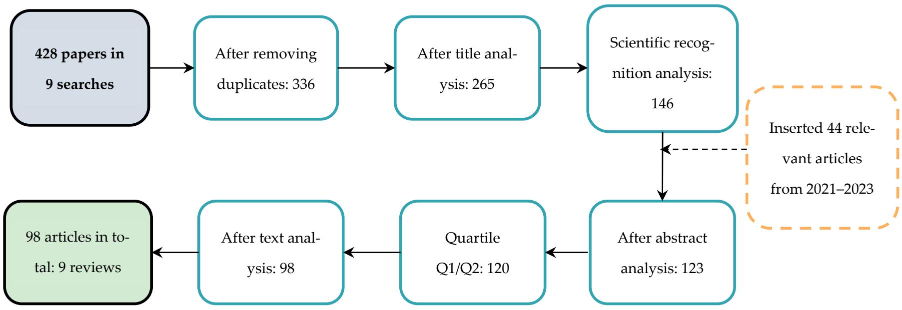

Figure 2. Number of articles in each stage of the method.

Regarding the researchers' countries of origin, 27 different nationalities were observed, with Italy being the most prominent, with 24 articles, representing 24.49% of the total sample. Figure 3 shows the number of articles per year and country.

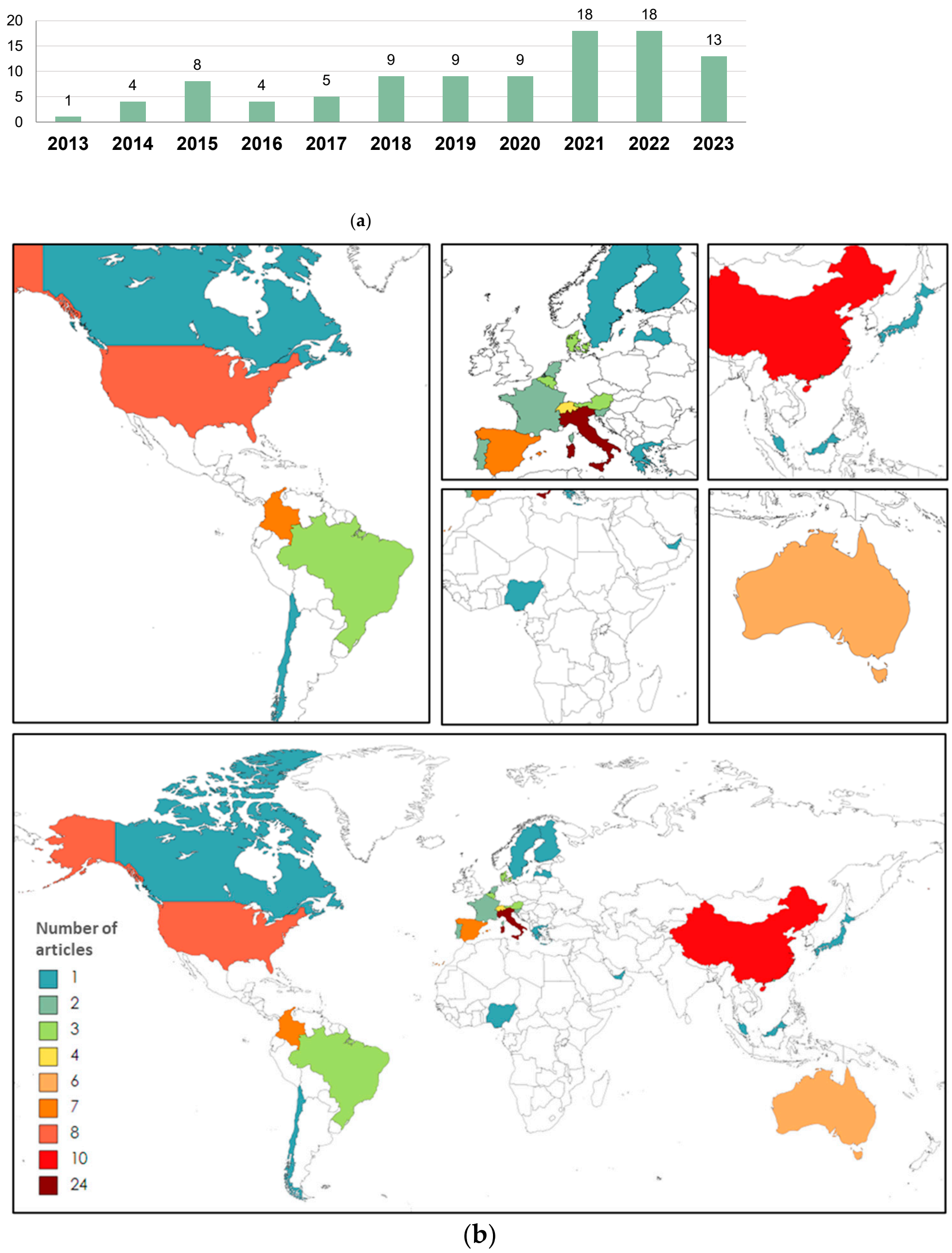

Figure 3. Number of articles by (**a**) year and (**b**) country.

Regarding the first author's educational institution, the institute with the highest number of published articles on the subject was the Universidad del Norte in Colombia, with five published articles. The second institution, which belongs to the country with the highest number of publications, Italy, was the University of Naples Federico II, with four articles found. Despite the concentration of articles in a few countries, as shown in Figure 3 (number of articles by (a) year and (b) country), a variety of institutions and researchers are interested in this subject.

In all, articles were found from 31 different journals that are between the Q1 and Q2 categories of the Scientific Journal Rankings. The journal with the highest number of articles found in this research was the Journal of Cleaner Production, with 27 articles, or 27.55% of the total. The second and third highest numbers of published articles were in Resources, Conservation and Recycling and Sustainability, with 13 articles each. Therefore, 3 of the 31 journals contained more than 50% of the total number of articles found, which means that there are a significant number of journals in this area with few publications on this topic. Figure 4 shows the results per journal, and Figure 5 shows the connection between countries and journals.

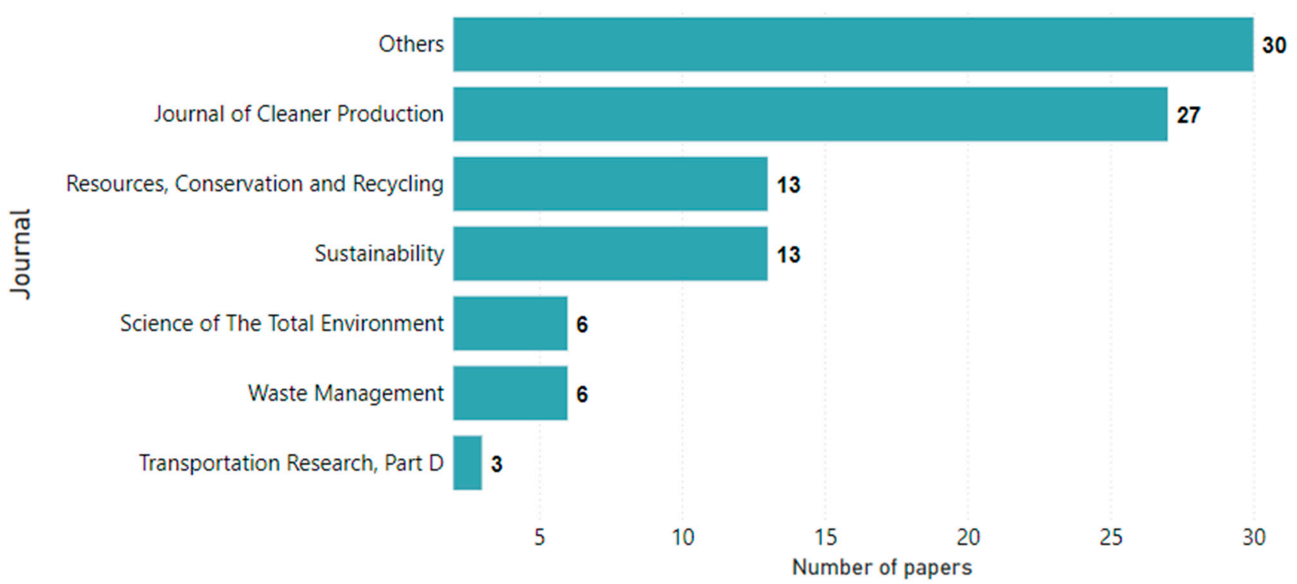

Figure 4. Number of articles per journal. Note: The "Others" group includes journals with two articles, namely Construction and Building Materials, Environmental Impact Assessment Review, International Journal of Pavement Engineering, Journal of Environmental Management Materials, and Transportation Research Procedia, and journals with one article, namely Baltic Journal of Road and Bridge Engineering, Case Studies in Construction Materials, Coatings, Environmental Research, Environments, Frontiers in Materials, International Journal of Life Cycle Assessment, IOP Conference Series: Earth and Environmental Science, IOP Conference Series: Materials Science and Engineering, Journal of Industrial Ecology, Journal of King Saud University—Engineering Sciences, Journal of Traffic and Transportation Engineering, Procedia CIRP, Processes, Recycling, Road Materials and Pavement Design, Sustainable Cities and Society, and Transportation Research Record.

3.3. Systematic Analysis

The following topics represent each criterion that was assessed in the papers found. At the end of this chapter, general considerations are made of the articles analyzed.

3.3.1. Type of Waste Incorporated

A variety of the materials applied come from industrial processes and include steel slag and fly ash, while others come from end-of-life recycling of materials such as tires, glass, or plastics.

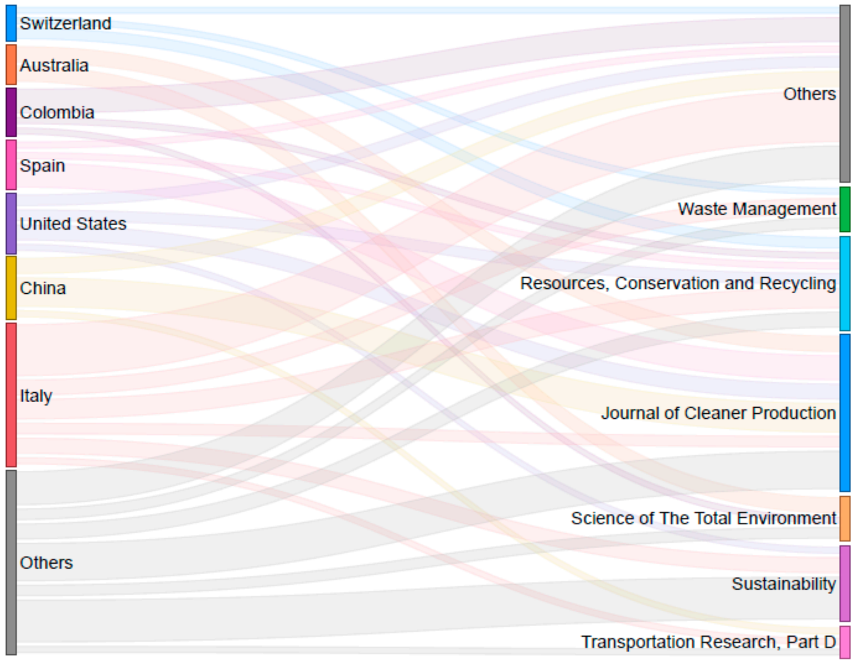

Figure 5. Relationship between countries and journals.

To summarize the data results, the materials were grouped by type. The types defined were reclaimed asphalt pavement (RAP) [33], construction waste (RCC) [34], slag, tire rubber [35], plastic, ash, asphalt shingles [22], glass [24], bio-oil [21], fibers, polymer [36], and municipal solid waste (MSW) [37]. The groups represented are described in the notes in Figure 6.

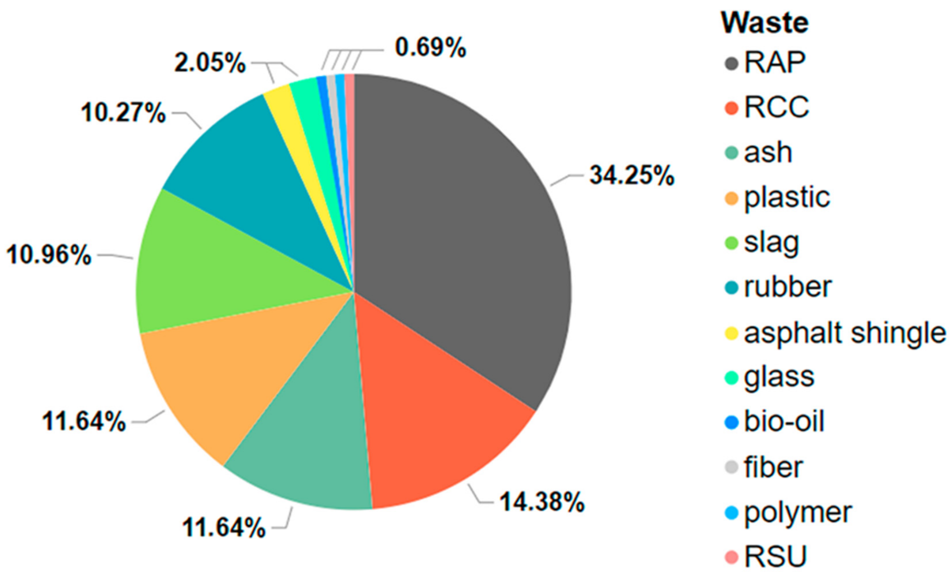

Figure 6. Most commonly used materials. Notes: The "Ash" group includes fly ash [38], MSW incineration [39], coal [12], and cellulose [40]. The slag group includes blast furnaces and foundry slag [41], electric arc slag [42], LD steel mill slag [43], and copper slag [40]. The plastics group includes plastic packaging films [44], polyethylene terephthalate (PET), polystyrenes and polyethylenes [45], microplastics [46], plastic waste [47], nylon, and reprocessed plastic [48]. The "Fibers" group includes textile fibers from tires [20], steel [7], glass [24], and lignin. The "RCC" group includes all construction waste, such as recycled aggregates [49], ceramic waste [15], jet grouting waste [50], and construction and demolition waste [34].

Figure 6 shows the percentage of articles that used each category mentioned. Although the different materials used were grouped together, the type most used among the articles researched was RAP. This category included papers that compared recovery techniques and those that considered the reuse of RAP in the asphalt concrete manufacturing chain.

3.3.2. Application to Paved Roads

To apply this waste to highways, we considered in what part of the flexible paved road structure the material was reused. Bernucci et al. [8] explained that a paved road is made up of layers that can be defined as follows:

- Surfacing: the outermost layer that absorbs the stresses caused by traffic; its purpose is to protect and waterproof the other layers, resist skidding, and offer a smooth, uniform layer that provides comfort to those traveling on it.
- Base: resists the deformations and stresses transmitted by the surfacing layer, distributing these stresses evenly over the inner layers. It also allows water to percolate in a controlled manner by means of drains.
- Subbase: also transmits the stresses of the upper layers to the lower ones. It is usually made up of less noble soil, so its main function is to reduce the thickness of the base, thus lowering the cost of base construction.
- Subbase reinforcement: its function is to improve the characteristics of the subbase to support the above layers and to stabilize the subbase layer.
- Subgrade: the foundation soil that will support the paved road. This soil is generally composed of material from the area in which the road is built.

Of the 98 articles analyzed, 76 examined the use of waste in the surfacing layer, also known as the asphalt layer, accounting for 77.55% of the total number of articles. Some studies used waste in more than one part of the paved road; 29 papers considered the base and subbase, and 3 considered the stabilization layer.

The next chapters analyze the articles on each stage of the LCA methodology. Only the 89 papers that applied LCA properly are analyzed.

3.3.3. First Phase of Life Cycle Assessment: Goal, Scope, Functional Unit, and System Boundaries

Of the 89 articles that applied the LCA methodology, 94.38% clearly stated the objective of the study. The papers that carried out a comparative analysis accounted for 94.05%, while the remaining papers carried out specific analyses. Among the studies that did not make a comparison, Deviatkin et al. [38] quantified the environmental impact of four alternative waste recycling methods, two of which were road construction and stabilization. Polo-Mendoza et al. [51] checked the maximum amount of RCA that can be incorporated into the asphalt layer from an environmental point of view. Huang et al. [52] estimated ways of mitigating greenhouse gas emissions in road construction in a province in China. Finally, Balaguera et al. [12], from a technical perspective, assessed the potential use of coal ash with caustic soda and conducted an LCA of the associated environmental impacts.

Among the studies that performed a comparative analysis, 59.49% compared the impacts of the road studied with those of a conventional road, 27.85% reflected on the differences between two or more paved road construction methods and types, and 12.66% compared the different possibilities for the destination of the chosen waste.

The ISO 14040 standard [9] defines a functional unit (FU) as a reference unit for quantifying the performance of a product system. This implies that when comparing two or more systems through LCA, the FU serves as a representative basis for drawing comparative conclusions. Importantly, in addition to defining the FU, it is necessary to establish the function performed by the product or system to make a fair comparison between the processes in the LCA. The FU provides a reference for quantifying the system's performance, but it alone is not enough to complete the first stage of the LCA. It is essential to consider the purpose of the product or system within a specific context and to align the FU with an appropriate reference flow to obtain valid results.

Regarding the declaration of the FU, 6.74% of the articles did not define the unit adopted [53]. Among the types of FU used, 55.42% of the articles used the linear extension unit, with the kilometer being the most used unit. Of the remaining articles, 27.71% used mass as the FU, 10.84% used area [54], and 4.82% used volume [46]. Unlike the other studies, the study of Yao et al. [55] compared LCAs by using the amount of wear between paved roads, with the FU being the wear of 4 cm of the asphalt layer.

It was possible to observe that most of the articles, 89.17%, used a unitary FU, i.e., 1 km, ton, cubic meter, or kilo. The remaining 10.83% adopted a specific FU according to the size of the paved road or even the amount of material used [17]. This lack of standardization makes it difficult to replicate the work elsewhere and is also another obstacle regarding comparisons between study results.

Defining the boundaries of the LCA means choosing which phases of the product's life cycle will be considered in the analysis. In summary, the phases of a paved road's life cycle are shown in Figure 7.

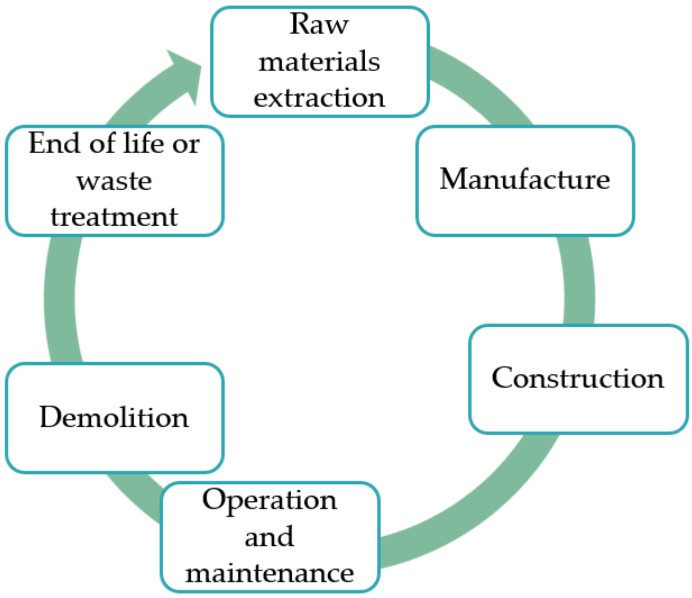

Figure 7. Phases of a paved road life cycle.

Regarding the boundaries adopted in the articles in this study, only one article did not define the boundaries adopted for the LCA [56]. Most of the articles considered the manufacturing phase of the materials; 44.32% of the articles used the "cradle-to-gate" limit. Approximately 11.36% extended to the construction phase [17], and 6.82% included the use and maintenance phase [57]. Approximately 30.68% encompassed the demolition phase, while only 4.55% evaluated the process from "cradle to cradle" [58].

Among the other studies, Sianipar and Dowaki [59] analyzed only the paved road maintenance phase, focusing on the types of restoration; they studied seven road sections in Indonesia to elucidate the correlations among environmental impact factors in road maintenance. The authors recommend that the LCA of paved roads should extend to the use phase to evaluate the appropriateness of integrating waste and whether such actions have fewer environmental impacts than conventional roads.

In the study carried out by Riekstins et al. [18], the limit of the system was considered from the construction of the paved road to the end of its useful life. The authors' aim was to investigate whether the environmental impacts over the life of the paved road would be significant if the extraction of raw materials was not accounted for. The results indicated that it is necessary to include all stages for a comprehensive environmental assessment. However, the authors noted that cost analysis can be carried out even when not all life cycle activities and processes are accounted for. This conclusion highlights the importance of considering an expansion of the system boundaries whenever possible to obtain better results and more complete assessments.

3.3.4. Life Cycle Inventory Analysis

In this step, the quality of the life cycle inventory applied was evaluated. This involved analyzing the type of data used and whether a global database was used or only primary data, i.e., data collected at the research site. We also looked at whether the authors carried out the LCA via market software.

Most of the articles used a combination of primary and secondary data, approximately 80.68%. Among the other papers, 15.91% used only secondary data, and only 3.41% used only primary data [60]. Importantly, adopting only secondary data and defining parameters based on the literature may not fully account for the article's objective, which is why it is necessary to employ specific criteria for choosing primary and secondary data with methodology and justification.

Of the articles found, 11.24% did not state whether they had used a global database and may have used only primary data and literature. Of those that used global databases, 72.46% used some version of Ecoinvent, 10.15% used GaBi [61], and 8.7% used PaLATE [62]. Of the remainder, 10.15% used local databases or reports, such as AusLCI, USLCI, and the Chinese Life Cycle Database (CLCD) [63].

The quality of the life cycle inventory is a delicate point regarding LCA work. Developing countries often do not have a database that provides all the information on the site studied. To address this challenge, articles should report on all the data that have been adopted and collected, with an emphasis on system flows that are unique to that research.

Having a quality inventory can improve the understanding of the work and provide a better understanding of the results and limitations, thus reducing the uncertainty of the information. For this reason, it is advisable to use primary data, stating the source and date on which they were collected, as some information may change over time. When a database is used, all relevant choices and adaptations adopted to suit the scope of the work must be reported.

LCA studies inherently involve a substantial volume of data, rendering manual calculations labor-intensive and susceptible to high error rates. Thus, specialized software proves advantageous for this application. The primary software options available for conducting LCA include SimaPro, OpenLCA, CMLCA, and GaBi. These programs differ primarily in terms of their intended objectives, language support, utilization of uncertainty methodologies, and integration with the Ecoinvent database.

SimaPro 9.5, designed for straightforward interpretation of inventory and impact assessment results, facilitates a detailed review of individual unit process contributions. It boasts multilingual support and, while not free, includes the Ecoinvent 3.9 and USLCI 2015 databases upon purchase. GaBi 9.1 focuses on processes rooted in industrial data, making it particularly relevant for applications in the automotive and electronics sectors, as well as modeling nonlinear processes [64].

Additionally, several free LCA software programs are available. OpenLCA 2.0 offers a modular platform for life cycle analysis and sustainability assessments. This open-source software can connect to an online database, but the Ecoinvent database must be purchased separately [19,21]. CMLCA 6.1, geared toward supporting the technical aspects of LCA, offers robust data analysis capabilities, including a comprehensive matrix algebra tool with matrix inversion and built-in methods for sensitivity analysis and uncertainty assessment [64].

Finally, a more simplified option is the Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE) 2.0, a spreadsheet-based LCA and LCCA program developed by the Consortium on Green Design and Manufacturing. This software is designed to evaluate the environmental and economic impacts of pavement and road construction [62].

Figure 8 shows the percentages of articles associated with different software programs.

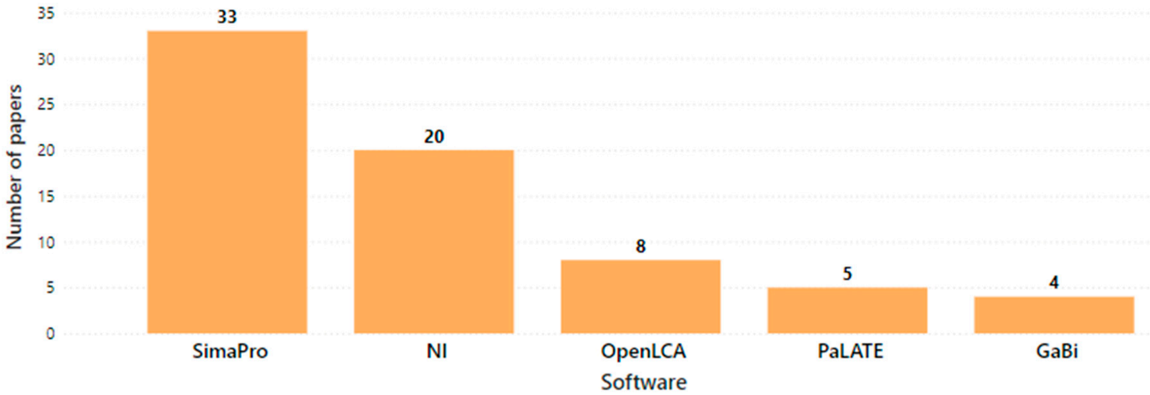

Figure 8. Software used by the studies found. Notes: NI—did not state or did not use software.

SimaPro is the most widely used software; it was the choice of 15 different nationalities analyzed in this research. Furthermore, the number of studies that did not use any software or did not provide information was also high, with half of these being articles from the last 3 years. In recent years, OpenLCA software, for example, has been updated with new features and is completely free. Approximately 70% of the studies reported which version of the software was used. A lack of information regarding the version used can interfere with results verification, especially for software that directly incorporates the database and has different impact assessment methods, such as SimaPro®.

Notably, the number of software programs used was greater than the number of articles; one study used more than one program to carry out its analysis [19]. As demonstrated by the authors, the use of multiple software programs, such as GaBi and OpenLCA, can initially offer a more comprehensive approach to assessing environmental impacts, allowing for the exploration of different perspectives and functionalities offered by each program. However, little difference was found in the results observed between these programs in relation to the impact categories analyzed.

Therefore, the choice of software should be more in line with the economic viability of access to the resource and ease of use.

3.3.5. Impact Assessment Methods and Categories

In the third phase of the LCA, the inventory data are categorized into specific impacts according to a selected methodology. The LCIA phase conducts a thorough interpretation of the inventory, aiming to establish a relationship between the values found in environmental impacts. Through a widely adopted method, it becomes possible to allocate inventory data to predetermined impact categories [7]. In each LCA, it is necessary to assess which categories are most relevant and which method is most suitable. The ISO standard [9] does not prescribe specific methods and categories, but it does mention the need to clarify the criteria and the process for selecting these elements. Some of the methods frequently encountered in the literature and their origins include ReCiPe (RIVM and Radboud University, CML, and PRé Consultants; Netherlands), CML 2002 (Centrum voor Milieukunde Leiden, Netherlands), Impact 2002+ (Switzerland), and TRACI (Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts, United States). During the analysis of the studies, applications of the methodologies widely used in the literature were noted. Figure 9 shows the LCA methodologies most commonly used in the evaluated paved road studies.

Most of the studies did not state or did not adopt a specific impact assessment method; instead, they individually analyzed only some categories, such as in the work of Movilla-Quesada et al. [40], in which only the greenhouse gas emissions of asphalt mixtures containing recyclable materials were verified. For example, in those studies that did not adopt a methodology, only one factor, such as the amount of toxic gas emissions, was calculated; this information was not categorized.

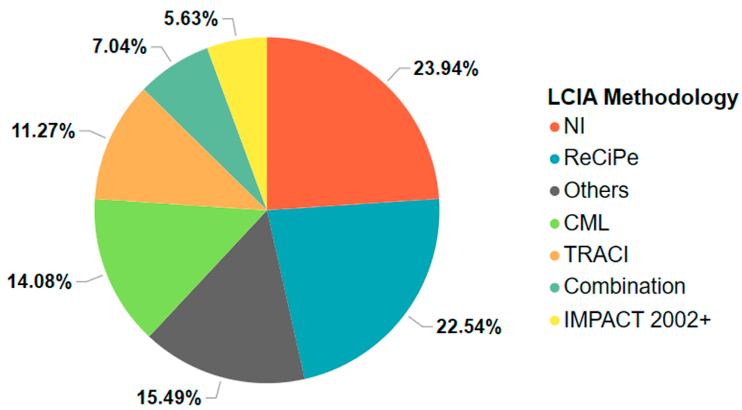

Figure 9. Most used life cycle impact assessment methodologies for paved roads. Notes: The "Other" group includes the BE2ST-in-Highways [63], ILCD (The International Reference Life Cycle Data System) [34], USEtox [37], Cumulative Energy Demand Method [13], and LCA4 Waste [65] methods. NI: did not state or did not use methodologies.

In the studies reviewed, the impact categories of acidification potential and global warming were analyzed more than other impact categories. Among the papers, 76.41% used midpoint categories, only one paper (1.12%) used only endpoint categories, and 22.47% used both categories.

Of the articles that used midpoint categories, approximately 35.29% analyzed only greenhouse gas emissions and energy and water consumption. This shows that some of the articles conducted only a superficial and simplified analysis of the LCA and did not explore other types of impacts relevant to environmental assessments.

Among the impact categories analyzed, 49 different categories were analyzed, with the most recurrent among the midpoint categories being global warming potential, acidification potential, and freshwater ecotoxicity potential and the most recurrent among the endpoint categories being climate change. Figure 10 presents the categories applied in more than three articles in descending order of the number of papers.

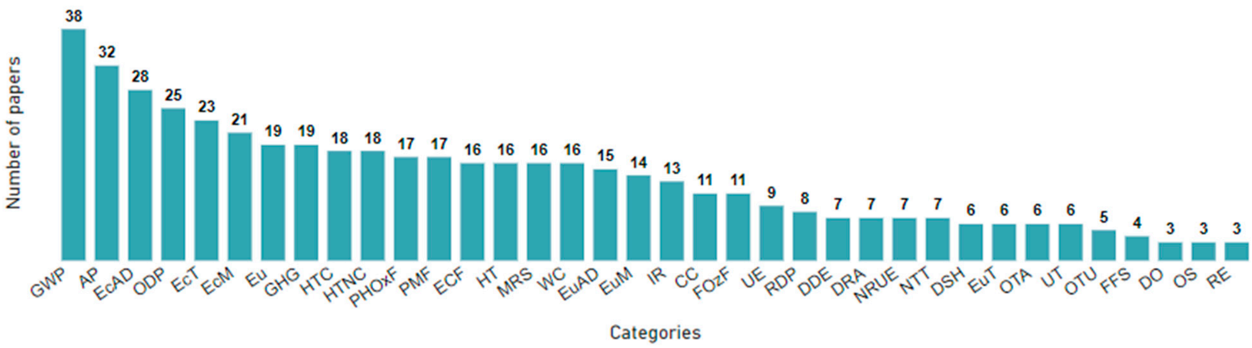

Figure 10. Some of the impact categories by number of articles. Notes: The acronyms presented are: Water Consumption (WC), Damage to Resource Availability (DRA), Damage to Ecosystem Diversity (DDE), Damage to Human Health (DSH), Respiratory Effects (RE), Inorganic Respiratory Effects (IRE), Organic Respiratory Effects (ORE), Fossil Fuel Scarcity (FFS), Mineral Resource Scarcity (MRS), Particulate Matter Formation (PMF), Photochemical Oxidizer Formation (PHOxF), Formation of Photochemical Ozone (FOzF), Greenhouse Gases (GHG), Climate Change (CC), Occupation of Agricultural Land (OTA), Occupation of Urban Land (OTU), Occupation of Soil (OS), Urban Land Cover (OSU), Acidification Potential (AP), Global Warming Potential (GWP), Resource Depletion Potential (RDP), Ozone Depletion Potential (ODP), Freshwater Ecotoxicity Potential (EcAD), Terrestrial Ecotoxicity Potential (EcT), Marine Ecotoxicity Potential (EcM), Eutrophication Potential (Eu), Freshwater Eutrophication Potential (EuAD), Marine Eutrophication Potential (EuM), Terrestrial

Eutrophication Potential (EuT), Leaching Potential (PL), Human Toxicity Potential (TH), Ozone Depletion Potential (DO), Air Quality (AQ), Ecosystem Quality (EQ), Radiation (R), Ionizing Radiation (IR), Hazardous Waste (HW), Human Toxicity (HT), Human Toxicity Carcinogenic Effects (HTC), Human Toxicity Non-Carcinogenic Effects (HTNC), Natural Transformation of the Earth (NTT), Land Use (UT), Energy Use (UE), Non-Renewable Energy Use (NRUE), and Renewable Energy Use (REU).

3.3.6. Waste Impact Allocation

When recycled materials or industrial byproducts are used to replace conventional materials and the impacts generated through the LCA are analyzed, the impacts of waste are often discussed. As the waste would generally be destined for landfill, most studies do not consider the environmental burden of its generation, considering that the material was a byproduct of other main production, as is the case with steel slag. Therefore, many authors consider "cutoff" allocation, which means disregarding all the impacts generated until the waste is used for a new process. Thus, only processes that are carried out exclusively with the waste are included in the LCA. The material generated by the previous process would be waste or rejects, which will continue to be produced as long as the industry manufactures the main product.

Most of the articles used the "cutoff" allocation, and approximately 64% of the papers disregarded the previous impacts of the waste studied. Some articles were also included in the LCA flow credit for not dumping the material in landfills. Among other articles, 20.22% did not make it clear what was considered, 11.24% considered the impact of waste production [66], 2.25% made an attributional [67] or economic allocation [68], and 2.25% included an LCA of more than one type of allocation [69,70].

Esther et al. [62] explained that the topic of allocation is quite controversial since authors in the literature consider it in different ways, and the ISO 14044 [10] standard recommends dividing flows as much as possible. In the research by Esther et al. [69], the authors created four different alternatives to analyze whether there is any difference in the final impacts of a slag used in paved roads in relation to different allocation types: one considering all the impacts related to the production of the slag; one using the cutting method; one using the "50/50" method proposed by Martin et al. [30] to divide the benefits between the steel and slag flows; and one expanding the LCA limits to include the impact that is being avoided by not exploiting natural materials.

The results of the research showed that the alternative with the most reasonable results was the cutoff method because attributing the impact of producing the main product to the waste makes this material unattractive, and taking some credit for the avoided impact creates problems in terms of conserving the mass of the LCA flow. Therefore, for this type of LCA, for the use of industrial byproducts or waste, the cutoff allocation method is recommended.

3.3.7. Sensitivity and Uncertainty Analysis

Only 35.96% of the studies carried out a sensitivity analysis, 32% of which did so in a simplified way or only for part of the process. Sensitivity analysis is a very important stage in the construction of an LCA study due to the uncertainty of the data, as secondary and bibliographic data are often used.

Regarding uncertainties, 88.76% did not carry out an analysis, 10.11% did so using the Monte Carlo method, and 1.13% (one paper) carried out an analysis by using a linear distribution [34]. As mentioned, data uncertainty can lead to results that do not correctly represent reality, and the use of uncertainty methods can make research more reliable.

3.4. Discussion

In the complete analysis of the 89 articles found, many divergences were found in the application of LCA methodology to paved roads. Most of the papers did not address some of the points that would be fundamental for a good presentation of results. Figure 11 shows the main points of greatest divergence between the studies and the number of articles for each topic. The number of articles that did not carry out a sensitivity analysis was the most significant factor. In addition, issues such as the clear definition of the scope and FU, the appropriate allocation of waste impacts, transparency of information on the data used, and the software used were also points often not addressed by the authors.

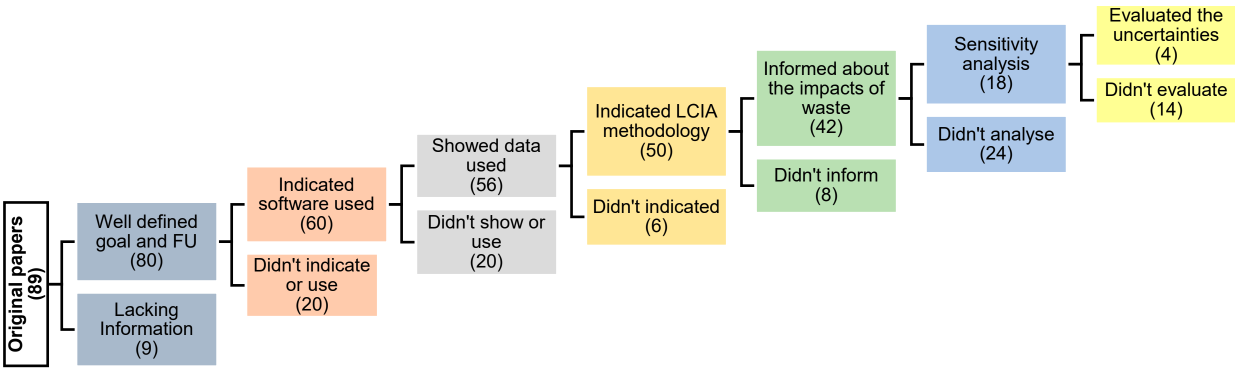

Figure 11. Points of divergence analyzed during the research. The number of articles on the topic is shown in parentheses.Importantly, in the articles reviewed, only materials that have been commonly used as waste were observed. There is already research that addresses globally discussed topics, such as microplastics, applied to paving [71]. However, there are still very few life cycle assessment analyses for this application. In the work of Ashish et al. [72], numerous applications of microplastics in asphalt and LCA studies for the plastics employed were explored. Nevertheless, the authors' conclusion underscores the need for additional data. While some studies have suggested the environmental benefits of incorporating waste materials, many of the cited research works rely on simplistic and potentially outdated models. Hence, there is a call for more comprehensive analyses utilizing the latest advancements in LCA methodology to inform and strengthen future LCA-based studies.

Considering all the steps recommended by the standard for a well-applied LCA, it is worrying to note that less than 5% of the articles followed all the recommendations. Although some steps are not mandatory, their absence can compromise the validity and comparability of the results and limit the usefulness of these studies for making informed decisions and advancing research in the field of LCA. It is therefore essential that researchers pay attention to these aspects and promote a more comprehensive and careful approach in their analyses.

The scientific community has been addressing other topics in recent years that have not yet been applied in the field of LCA for pavement. One of these topics is the application of artificial intelligence in pavement construction. There are already some studies on this application in other engineering areas, such as the work of Han et al. [73], which presented a machine learning model for predicting the elasticity modulus of concrete formulated with recycled concrete aggregate. Another review work highlights the various studies on the application of AI in LCA, and the authors concluded that these techniques support data collection in LCA studies, but there is a lack in the literature regarding the combination of these methods into an integrated model [74]. By observing these works, one can identify various opportunities for the application of this tool in the LCA methodology for pavement.

Therefore, a structural format should be followed to carry out higher-quality research that allows the work to be replicated in different situations. The authors' intention with this proposal is to support improved processes related to LCAs applied to the use of waste in paved road construction and promote the start of a discussion on standardizing this process.

4. Guidelines for Future Work

The following topics address the most relevant points of the LCA stages that should be considered. Figure 12 presents a summary of the guidelines, which were developed based on the main shortcomings identified and the best practices observed.

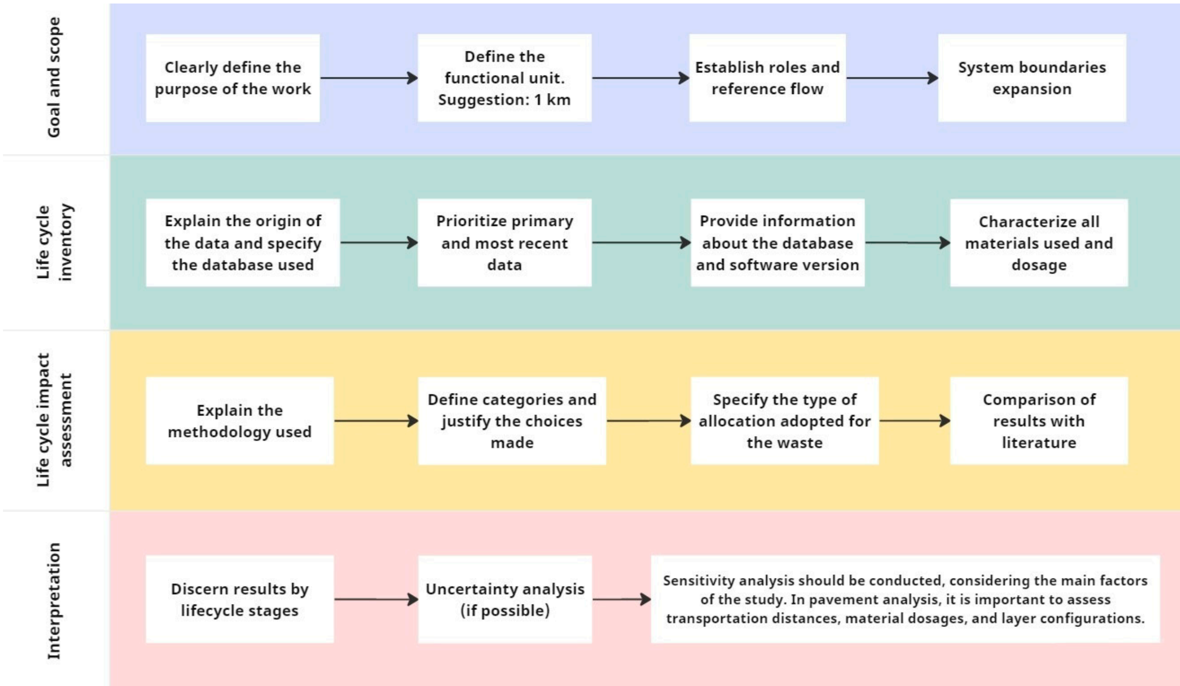

Figure 12. Summary of the guidelines.

4.1. Defining the Objective and Scope

When defining the objective of the work, the purpose of the research must be clarified at the beginning of the methodology. This includes determining whether the study aims to quantify the impacts generated by one or more types of paved roads or whether it seeks to make a comparison between them. The desired result at the end of the research must be stated.

Regarding system boundaries, it is important to provide details of what is considered within them. This includes the phases of the life cycle of the object of study and the input and output flows. It is essential to define what the foreground and background of the system will be, i.e., which processes will be obtained from primary sources and which from secondary sources. The boundaries adopted should be as broad as possible and should preferably be indicated by means of a diagram to facilitate understanding. Furthermore, the assessment should extend at least up to the use and maintenance phase to check whether the durability of the paved road with integrated waste impacts the LCA results. This will help ensure a comprehensive and accurate analysis of environmental impacts throughout the paved road's life cycle.

It is important to clarify the FU adopted in the study and the factors directly related to it. This means providing basic information on the size and composition of the paved road, such as the width of the road, the thickness of the layers, the mix of materials, and the percentage of waste used. In addition, it is necessary to choose a similar FU with similar characteristics for comparisons. The establishment of the function of the paved road or material and the reference flow is a prerequisite for this process.

In this work, we recommend using 1 km of paved road with one lane as the FU, as it is the most widely used among all the studies evaluated and can serve as a comparative source with relative numbers for other research. For the function of the paved road, a traffic volume and road class can be established as a reference. In the case of an LCA of a single raw material, limited to the cradle-to-gate scope, an FU of 1 kg of material is suggested, accounting for the specific characteristics of that product, such as strength, compactness, humidity, and void ratio.

4.2. Life Cycle Inventory

The data used in the study should be clearly stated, and the authors should provide quantities and characteristics of the materials whenever possible, especially in cases where global databases are not used. It is important to detail the source of the data so that its quality can be assessed and associated with some level of uncertainty. The use of primary data, which better represent the local reality of the research, is recommended. If secondary sources are used, the stages that were accounted for and adaptations made to suit the scope of the work should be stated.

If databases were used, the source and version of the database used should be stated so that it is possible to reproduce the research based on the same criteria. If any software was used for the analysis, the program and its version must be mentioned. If no software was used, a detailed determination should be made regarding the method for calculating the impacts, and the results should be presented in tables, demonstrating the intermediate process. We recommend using widely used software, such as OpenLCA, which is a free tool, or SimaPro, to reduce errors resulting from manual calculations. If any software has been employed, the version used during the research should be indicated.

4.3. Impact Methodology

It is essential to provide information on the impact methodology adopted, including its specific version, as well as considerations on the midpoint and endpoint categories. It is necessary to detail all the impact categories chosen and justify the selection of each one. Some categories may be more relevant to certain types of waste due to their chemical composition or unique characteristics, so they should be considered according to the scope of the work.

The method adopted for allocating the impacts of the waste should be stated, such as the "cutoff" approach, which considers only the processes related to the other materials; furthermore, the processing stages of the waste considered should also be indicated. Clarification should be given regarding any impacts that have been discounted due to the exclusion of any process, such as sending the waste to a landfill or extracting natural resources.

If the approach adopted is not of the "cutoff" type, it is important to state whether all the impacts related to this waste since its generation are accounted for and whether any allocation made relates to the product of origin, whether economic or attributional. Descriptions of the approach to allocating impacts should provide clear and detailed information on the decisions made, accounting for the specifics of the waste under study, any assumptions, and the criteria used to allocate impacts.

Reference works that address the same line of research as the study in question are recommended, thus allowing a comparison of the data and methodological choices made.

4.4. Interpretation

In the interpretation phase of an LCA study, it is important not only to present the results of the impact categories but also to assign responsibility for the impacts to each part of the flow analyzed. This process should be performed by dividing up the construction stages, which include obtaining the materials, transportation, manufacture, construction, use, demolition, and the end of the paved road's life. This approach makes it possible to understand the main contributors to the environmental impacts associated with the paved road under analysis.

Identification of the largest impactors in each stage enables targeted efforts that can mitigate impacts through specific actions in each stage of the paved road's life cycle. This detailed analysis and assignment of responsibilities contributes to a more effective approach for reducing environmental impacts and helps inform decisions regarding the development of sustainable strategies in paved road construction.

Developing a sensitivity analysis can provide even more information for a high-quality LCA study to identify factors that can influence the results. Two factors that often vary in work involving the use of waste are the local availability of materials and the percentage of waste incorporated. It is therefore important to consider the transportation distances of the raw materials in the construction phase of the road and the quantities of the materials in the paved road layers.

Given that the LCA methodology involves numerous subjective choices, it is recommended to carry out an uncertainty analysis to obtain more reliable and appropriate results. Uncertainties are inevitable, and neglecting them when analyzing results can lead to biased or even incorrect conclusions. The consideration of uncertainties becomes more important in studies that include complex and long systems.

In the studies found, uncertainties can be attributed by applying the pedigree matrix to all data flows and using the Monte Carlo method to assess the variation in results. In this way, it is possible to estimate the margin of uncertainty associated with the results obtained.

By considering these sensitivity and uncertainty analyses, a more comprehensive understanding of the robustness and reliability of the LCA results is gained, allowing for a more accurate and informed interpretation of the environmental impacts associated with the use of waste in paved road construction.

Finally, at the end of the interpretation stage, it is essential to emphasize that the investigation must go beyond merely identifying the main points of impact. In addition, it is essential to address alternatives to the results obtained in the study by proposing concrete actions for their practical implementation, rather than remaining solely theoretical. These improvements can be extended to various topics within the scope of the study, including updates to the vehicle fleet, adjustments to materials delivery routes, shifts in suppliers, exploration of alternative energy sources, and more. By incorporating these enhancements across these diverse areas, the research aims to foster a comprehensive and refined analysis of environmental impacts.

Such results also have relevance in the context of carbon credits. LCA can assess the environmental impact of pavements, encompassing carbon emissions, across their entire life cycle. This methodology identifies crucial emission points and opportunities for reduction. Carbon credits become relevant when complete emissions elimination is challenging [75]. They provide financial compensation for emissions through activities such as reforestation or renewable energy initiatives [76]. Consequently, the potential for producing substantial results is vast.

5. Conclusions

The aim of this systematic review was to analyze studies that have applied LCA to the integration of waste in paved roads. Many similarities in these studies were found; however, certain gaps in the provision of data in the LCA stages could indicate the appropriateness of the study results.

The study results include the following observations:

- There has been an increase in research over recent years regarding the application of LCA to paved roads.
- Most of these studies have looked at the application of RAP, and there is ample opportunity to carry out research into various other types of waste. The studies primarily focused on the top layer of the paved road, asphalt concrete, which was evaluated in more than 75% of the studies.
- There are several information gaps in the studies found, such as the absence of a clearly defined objective, inadequate disclosure of software version and database information, insufficient indication of methods applied, a lack of information about follow-up procedures, and an absence of guidance regarding waste allocation. Addressing these gaps has the potential to enhance the tool's applicability within this research area.

It was possible to identify a variety of FUs, types of data, methodologies, and impact categories, as well as types of systems and forms of allocation. Most of the information is presented in different ways; thus, it is not feasible to compare the work and replicate the research.

Therefore, there is a need to determine a type of standard method to be followed in the application of LCA to paved roads so that studies can be compared and the application of these results increased. The guidelines presented in this study provide a starting point for future studies, thus enabling higher-quality data to be generated. These data can then be used by more researchers in the field as a basis for practical applications.

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