Review

A Review on Life Cycle Assessment of Pavements in Brazil: Evaluating Environmental Impacts and Pavement Performance Integrating the International Roughness Index

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Abstract: This article addresses the limited understanding of the landscape regarding Life Cycle Assessment (LCA) in Brazilian pavement infrastructure. It provides an overview of LCA's application in assessing the environmental effects of pavements while exploring the use of the International Roughness Index (IRI) as a performance criterion to assess environmental consequences and pavement performance. A comprehensive search for relevant quantitative LCA studies, published from 2013 to 2023, was conducted across several bibliographic databases, following ISO 14040 standards. A total of fourteen case studies were analyzed, providing insight into frequently used software, databases, Life Cycle Impact Assessment (LCIA) methods, and functional units. Furthermore, global warming or greenhouse gases (GHG) were the most frequently used environmental indicators, while materials, transportation, and construction were the most inventoried life cycle phases. However, the search also highlighted limitations, including the availability of Brazilian data and scope definition. Nevertheless, a quantitative comparison between conventional pavements showed a low standard deviation. The scenarios studied demonstrated that using recycled materials in pavement construction and employing high-strength materials in layers and subgrade can reduce environmental impacts. In conclusion, these findings contribute to the development of sustainable pavement practices in Brazil and highlight the need for further research to validate current findings and address existing gaps.

Keywords: Life Cycle Assessment (LCA); environmental impacts; pavement performance; International Roughness Index (IRI); sustainability; limitations

1. Introduction

Driven by economic development and social connectivity, road transport has emerged as the primary method of cargo transportation within Brazil. Having an extensive network of roadways spanning 1,720,909 km [1], this vast man-made infrastructure unquestionably carries a significant burden of environmental consequences. Notably, as of 2021, the Brazilian transportation sector was responsible for an astonishing 204 million tons of carbon dioxide equivalent (CO_2 eq) emissions [2].

As cities across the globe keep expanding, the need for efficient and sustainable infrastructure increases. Among the critical components of urban development, pavement systems play a fundamental role in ensuring smooth transportation networks. However, the environmental impacts associated with pavement construction and maintenance cannot be overlooked. Extraction of natural resources, usage of petroleum derivatives, fuel burning to obtain energy, and land allocation are all examples of these impacts.

To address the urgent need to slow the pace of climate change and prevent biodiversity loss, stakeholders are recognizing the importance of transformative measures in pursuit of sustainability. Achieving sustainability requires not only technological innovations and solutions from companies but also behavioral changes and social innovations. Companies must adopt a comprehensive life cycle view to incorporate environmental, social, and

economic considerations into their strategic and operational decisions. LCA is a primary technique that supports such decision-making processes.

In the context of sustainable pavement design and construction practices, understanding and quantifying the environmental impact associated with pavements throughout their life cycle stages is crucial. This paper's objective is to provide an overview of the LCA methodology and its application in evaluating the environmental impacts of pavements in Brazil. By doing so, it aims to equip the academic community and stakeholders with current methods, knowledge, gaps, and limitations in this field. Additionally, the potential integration of the International Roughness Index (IRI) as a performance criterion is explored as a means to mitigate environmental impacts and enhance long-term resilience.

The bibliographic search was conducted using several platforms, including the Conference on Transportation Research and Education (Congresso de Pesquisa e Ensino em Transportes—ANPET in Portuguese), the National Road Conservation Meeting (Encontro Nacional de Conservação Rodoviária—ENACOR in Portuguese), the National Meetings of Production Engineering (Encontros Nacionais de Engenharia de Produção—ENEGEP in Portuguese), and the Production Engineering Symposium (Simpósio de Engenharia de Produção—SIMEP in Portuguese). Additionally, the search included repositories from prominent institutions such as the University of São Paulo (USP), the Federal University of Rio de Janeiro (UFRJ), the Federal University of Santa Catarina (UFSC), and the University of the Sinos River Valley (UNISINOS). Brazilian journals such as *Sustainable Mix* (Mix Sustentável in Portuguese) and *Transportation* (Transportes in Portuguese) were also included in the search. Furthermore, academic databases such as SciELO Brazil, Web of Science, and Scopus were utilized for this comprehensive search.

Once the decision was made regarding the bibliographic research databases, the search was carried out using pertinent keywords related to pavement LCA, both in Portuguese and English. The selected keywords included: "Life cycle assessment", "LCA", "pavement", "road", and "Brazil". The time frame was limited to publications released between January 2013 and July 2023, exclusively within the geographical scope of Brazil. From the extensive collection of search results, only documentation about quantitative pavement LCA studies adhering to the ISO 14040 standards was considered for further evaluation and analysis [3].

This paper is organized into five sections, including an introduction. Section 2 provides a comprehensive overview of the LCA methodology. In Section 3, a detailed exploration of LCAs applied to pavements is presented, discussing the various stages and approaches associated with them. This section is further subdivided into two parts: firstly, an examination of observed gaps and limitations; and secondly, an exploration of the Pavement–Vehicle Interaction (PVI) effect and its correlation with the IRI (International Roughness Index), as well as the potential application of this index. Moving on to Section 4, an analysis and comparison of Brazilian quantitative pavement LCA studies resulting from the aforementioned bibliographic research is conducted. This section is divided into five subsections, providing a detailed analysis of the applied LCA methods, specific pavement designs under evaluation, and the findings of each study. Finally, Section 5 presents the study's conclusions and proposes future research.

2. Life Cycle Assessment Methodology

LCAs originated in the late 1960s as Resource Environmental Profile Analyses (REPAs). Later in the 1970s, as oil became less abundant, the importance of researching alternative sources of energy and their environmental implications grew. This resulted in the LCA's applicability being extended to a wider range of products. Eventually, the term "life cycle assessment" was first used in the United States in 1990 [4].

In Brazil, LCA studies began in the 1990s, leading to the foundation of the Brazilian Life Cycle Association (Associação Brasileira de Ciclo de Vida—ABCV in Portuguese) in 2002. Since then, numerous articles have been published using the LCA technique for case studies, evaluations of production processes, and comparisons of materials or processes [5].

The LCA is a methodology used to assess the environmental performance of a product or service throughout its life cycle, from the extraction of raw materials to its final disposal. Environmental metrics are quantified to determine the potential impact of emissions on the environment, humans, and resources [3,6].

The International Organization for Standardization (ISO) has developed standards for LCA in its publications: ISO 14040 and ISO 14044. The first refers to the principles and structure of an LCA, while the second refers to the requirements and guidelines for an LCA. These specifications are published in Brazil by the Brazilian Association of Technical Standards (Associação Brasileira de Normas Técnicas—ABNT in Portuguese) as ABNT NBR ISO 14040 [3] and ABNT NBR ISO 14044 [7].

The ABNT [3] defines the LCA as a "compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle". It is subdivided into four parts: (1) goal and scope definition; (2) inventory analysis; (3) impact assessment; and (4) interpretation. However, the structure is not fixed due to the iterative nature of the LCA process. The outcomes of one phase are incorporated into subsequent stages, and interpretation is continuous throughout the evaluation.

Overall, LCA is a valuable methodology for evaluating the environmental impacts of products and services. However, while interpreting results and making decisions based on them, it is essential to keep the methodology's strengths and limitations in mind.

Some of the main strengths include: (a) comprehensive evaluation, LCA allows a systematic assessment of environmental impacts across a product's or service's entire life cycle, covering upstream and downstream activities from raw material extraction to disposal [8]; (b) tool for decision-making, LCA adheres to established guidelines and frameworks, ensuring transparency of results across different products and services, and by taking an inclusive and holistic approach, LCA contributes to a more open-minded perspective [9]; (c) identification of improvement opportunities, by identifying hotspots and areas of high environmental impact, LCA can assist in identifying opportunities to enhance a product's or service's environmental, economic, and social performance, and thus contribute to establishing public policies [6].

The following are some of the frequently mentioned limitations: (a) data quality and availability, LCA relies heavily on these parameters, if the data are unavailable or unreliable, it may lead to inaccurate or incomplete results, and it is important to ensure that inventory data are reliable and specific to the relevant regions being studied [10]; (b) compatibility, the scope and system boundaries can be difficult to define, leading to variability in results and making it challenging to compare results across different studies [11]; (c) complexity and uncertainty, the methodology requires specialized expertise and software which can make it challenging for non-experts to understand and apply, additionally, subjective judgment is involved in the selection of impact categories and weighting factors which can affect the reliability of the results [12].

Despite its limitations, the application of LCA has been helpful in assisting stakeholders worldwide to achieve their sustainability goals. LCA has become a valuable tool in developing public policies and promoting the sustainable development of products and services. In Brazil, while the LCA methodology is still relatively new, studies have mainly focused on the agro-industry [13], energy [14], and construction sectors [15]. There is also a growing trend toward applying LCA in the transport infrastructure sector.

3. LCA of Pavements

The environmental impacts of pavements can be significant and wide-ranging. Clearing and grading land for construction can cause habitat destruction and wildlife displacement. The extraction of natural resources such as crude oil, sand, and gravel is required to produce paving materials such as asphalt and concrete. This extraction procedure may have consequences for the environment, such as habitat destruction, soil erosion, and water pollution. Furthermore, the transportation of pavement materials produces large GHG emissions, contributing to global warming [16].

The use of heavy equipment during construction results in the emission of carbon dioxide (CO_2), nitrous oxide (N_2O), and other pollutants; it also contributes to noise pollution, which can have negative impacts on the health of both wildlife and humans. Once built, the runoff from the pavement can contain pollutants such as oil, grease, and heavy metals, which can be harmful to aquatic ecosystems and water quality [17]. Furthermore, the pavement's tendency to absorb and retain heat contributes to the urban heat island (UHI) effect. This phenomenon increases energy consumption for cooling buildings and intensifies the impacts of heatwaves on human health [18].

A life cycle assessment can be used to identify specific impacts associated with different stages of the pavement's life cycle and propose strategies for reducing those impacts. According to the ABNT [3], there is no standardized definition of the stages to be considered in a product's system. However, several authors have agreed that the phases of the pavement's life cycle are: (1) material extraction and production; (2) construction; (3) use; (4) maintenance; and (5) end-of-life [10]. This boundary approach is referred to as cradle-to-grave, which provides a comprehensive evaluation of the environmental impacts associated with this infrastructure from start to finish [19].

There are different boundary approaches that can be taken in a pavement LCA study. A cradle-to-gate or cradle-to-site LCA includes all activities from raw material production to road construction [20], whereas a gate-to-gate LCA focuses on a single process within the production chain [21]. However, the definition of the activities in an LCA is a procedure that lacks consensus among the pavement LCA community. Therefore, the availability of relevant data and the intended scope and objective define the approach to LCA to be applied.

3.1. Gaps and Limitations of LCA Studies of Pavements

The life cycle approach is a methodology that considers all stages of a product's life, understanding that a large number of factors can have an effect on the product system under analysis. However, the complexity of this study often leads to the omission of certain areas, disregarding their potential influence and leaving quantitative gaps in the assessment methodology, thus compromising the accuracy of the findings and the validity of the conclusions. In that matter, Santero et al. [22] and Azarijafari et al. [11] identified some areas that need further research.

One of these areas is the earthworks. Barandica et al. [23] argue that this construction activity has the most GHG emissions, accounting for 60–85% of the emissions in construction. However, its incidence is relative to the project's work site orography.

Another gap is the consideration of traffic delays. When a road or highway is under construction or repair, these operations can cause traffic delays in the working zone (WZ). This increases GHG emissions and air pollutants from idling vehicles. Currently, there are few studies that have taken this particular factor into account. Nevertheless, the importance and growing interest led the authors to consider WZ traffic management as a separate life cycle stage to highlight its influence. Research has shown that the influence of WZ traffic management can vary significantly depending on the project's traffic volume and management strategies [24].

The use phase also presents several gaps in LCA studies. Concrete carbonation, pavement lighting, and leachate are some factors that can affect environmental impacts. Likewise, the Massachusetts Institute of Technology Concrete Sustainability Hub has found that the two main contributors to the use-phase environmental impacts come from the albedo and the PVI [25]. Albedo, or the reflectivity of the pavement surface, can affect the absorption of solar radiation and contribute to the UHI effect, whereas the PVI describes the effect of pavement structural and surface properties on vehicle fuel consumption. As a result, given the traffic demand and life span of pavements, several authors have claimed that the use phase contributes significantly to the environmental impacts throughout a pavement's life cycle [26].

Finally, the disposal or end-of-life phase of pavement is also critical, as it determines the final impact on the environment. During this phase, there are three possible courses of action for the pavement: it can either be demolished and disposed of in a landfill, demolished and recycled, or left in place as a foundation for a future pavement structure. It is important to account for recycling in order to prevent double-counting of both the impacts and benefits between producers and users. Unfortunately, this stage is often overlooked [22].

In addition, restricting the analysis of pavement options to only their environmental impact, without taking economic and social factors into account, can limit the scope of the analysis. This narrow focus can result in the selection of pavement options that are environmentally friendly but are not cost-effective or do not meet societal needs [27]. Therefore, pavement LCAs must be complemented with other studies to ensure that decision-makers can make more informed decisions that consider all relevant aspects of the pavement options being evaluated [3].

3.2. Incorporating Pavement Performance Indicators in LCA Studies

Pavement performance refers to the ability of a pavement structure to fulfill its intended functions over its life span, considering factors such as durability, serviceability, safety, and user satisfaction. Several aspects can influence pavement performance, including material properties, design characteristics, construction quality, traffic loads, environmental conditions, and maintenance practices [28]. Similar to LCAs, the evaluation of pavement performance serves as an invaluable tool for informed planning and decision-making processes.

Various tools and indicators have been adopted to measure and quantify pavement performance, such as cracking, rutting, the Present Serviceability Rating (PSR), and the Pavement Condition Index (PCI) [29]. However, the most commonly used indicator is the International Roughness Index (IRI). It quantifies the smoothness of a pavement surface and is typically measured in m/km, mm/m, or in/mile. A higher IRI value indicates a rougher road surface, while a lower IRI value signifies a smoother road surface [30].

During the use phase, the IRI assumes a critical role in assessing pavement performance. It has been demonstrated that there is a correlation between increased IRI values and higher fuel consumption [31]. In other words, increased vehicle bouncing is caused by increased pavement roughness, resulting in increased fuel usage. It should be mentioned that, as Santos et al. [32] claim, the use phase carries the greatest percentage of environmental impacts in a pavement's life cycle. Therefore, even a small increase in roughness can have a significant effect.

Furthermore, the PVI effect, with the IRI as a key component, emerges as the primary contributor during the use phase. The PVI effect encompasses various factors, including pavement surface texture, changes in roughness (characterized by the IRI), and deflections in the pavement structure. Among these factors, the latter two have the most significant impact on PVI [33]. However, determining the relative influence of these two factors within an LCA is challenging. The PVI effect strongly depends on variables such as traffic level, truck volume, and speed limits [34], making it difficult to ascertain which factor holds greater influence on the LCA outcomes.

In recent years, there has been a focus on developing models to analyze the structural response under dynamic loading aiming to determine excess fuel consumption for pavements with asphalt surfaces. Various modeling methods, including mechanistic, deep-learning, and finite-element modeling, have been employed [35–37]. Research has indicated that load, temperature, and speed are the most influential factors in the dissipation of vehicle kinetic energy in the pavement structure or rolling resistance. These models can evaluate the LCA's use phase and provide decision-making tools for pavement maintenance and rehabilitation (M&R).

Moreover, the IRI can serve as a valuable performance criterion in LCA studies, complementing existing categories such as GHG emissions, energy consumption, and costs.

This manner of utilization aims to determine whether the use of alternative materials, maintenance techniques, and variations in the structural design of pavements can achieve a comparable level of functionality and structural integrity when compared to a conventional new pavement. It is important to note that using different materials or making changes might introduce physical and engineering differences, which may impact pavement performance even if construction processes are carried out correctly. Therefore, this IRI approach serves to evaluate the potential environmental benefits and performance trade-offs associated with these variations.

Some case studies have successfully incorporated IRI as a performance criterion, going beyond its use solely for calculating extra fuel consumption during the use phase. For instance, Chong et al. [19] have used the concept of IRI trigger value as an independent variable. This value represents the maximum IRI threshold before maintenance, rehabilitation, or reconstruction is required, aiming to maintain favorable rolling conditions throughout the project's life span.

A lower or more stringent IRI trigger value implies the need for more resurfacing during the life cycle, resulting in an increase in environmental burdens associated with materials, construction, and congestion. Conversely, a higher IRI trigger value may alleviate the aforementioned burdens but could lead to increased vehicle operation-related burdens. This is because vehicles traveling on rough pavement consume more energy compared to those on smoother surfaces.

Their study revealed that certain pavements exhibit optimal thickness and IRI trigger values, which are influenced by traffic levels. These pavements generally offer a more environmentally friendly solution without requiring reconstruction during the analysis period, compared to pavements that do require reconstruction. However, excessively conservative designs were found to have higher energy consumption and GHG emissions [19].

The previous statement is consistent with the findings of Yang et al. [38]. They observed that traffic volume had a major effect on the breakeven point, which is the point at which the additional fuel consumption caused by accelerated pavement deterioration offsets the initial savings gained from utilizing recycled materials. At high traffic volumes, the energy demands during the use phase could surpass the energy savings from the material production phase, even with a slight reduction in the pavement's life span. This determination was made by comparing the environmental impacts across the life cycle while considering the varying IRI rates associated with each scenario.

Overall, the integration of IRI progression with LCA analysis could provide a more holistic view and enhance understanding of the environmental impacts of transportation engineering. However, a significant challenge comes from using the IRI, as predicting it with maximum precision remains a major research focus due to its complex sensitivity to numerous factors impacting pavement performance during both construction and usage [39]. Several IRI evolution models have limitations, including complex equations, plenty of variables, difficulties in data collection for variables, and a short prediction period [40]. Ongoing research and further improvement are essential to enhancing the precision and practicality of this approach.

4. Case Studies of Quantitative LCA Studies of Pavements in Brazil

In Brazil, some studies have examined the environmental impacts associated with pavement construction. However, the lack of consensus in the phases, impact categories considered, software utilized, databases employed, functional units adopted, and the scope of the inventory have made it challenging to evolve this methodology in the road infrastructure area. To address this, an extensive review of existing literature was conducted. This review identified a total of 14 quantitative pavement LCA studies: 8 sourced from the Web of Science, 2 from Scopus, 2 from USP, 1 from the *Sustainable Mix* journal, and 1 from the ANPET. To gain a comprehensive understanding of the variations and similarities among these studies, an in-depth analysis was performed on the applied LCA methods, the specific pavement designs evaluated, and the results of each research study.

4.1. Scope Definition for LCA Development

The primary focus of an LCA is to encompass the entire life cycle of a product or service. As mentioned earlier, this concept applies to pavements as well, typically involving five phases: material extraction and production, construction, use, maintenance, and end-of-life. To provide a more comprehensive analysis, a sixth phase has been introduced: the transportation of materials.

Furthermore, in LCAs, a range of environmental indicators are available to evaluate the environmental impact of a product or process. The selection of relevant indicators depends on the study's objective and scope. The most commonly used indicators include acidification, global warming, resource depletion, ozone depletion, human toxicity, respiratory inorganics, ionizing radiation, photochemical ozone formation, eutrophication, ecotoxicity, and land use [41]. In line with these considerations, Table 1 summarizes the life cycle phases and environmental indicators examined in each study.

The initial review of Table 1 reveals a pattern in which either global warming or GHG appears as a regular environmental indicator throughout all the studies. Among the most commonly used indicators, energy use, acidification, and eutrophication stand out. Land use and ionizing radiation are two environmental indicators that have not been considered in any of the studies conducted. This is intriguing, given that land use is a central topic of discussion during the construction of new roadways, mainly due to its potential for ecosystem degradation, resulting in the loss of vegetation cover and decreased biomass productivity.

Additionally, it has been observed that there are two different tendencies regarding the environmental indicators analyzed in Table 1. Firstly, half of the studies opted for a simplified quantitative analysis, focusing on up to three environmental indicators. In this group, the presence of energy use and either global warming or GHG as primary indicators is consistent. In contrast, the remaining studies pursued a more comprehensive approach, carrying out detailed quantitative analyses covering up to eight environmental indicators. While these studies exhibited diverse combinations of environmental indicators, a noteworthy consistency appears in the inclusion of acidification, global warming, and eutrophication in their research.

In terms of pavement life cycle phases, none of the examined studies included the entirety of all five phases. However, the inclusion of the transportation of materials was a common input throughout all references, either as a separate phase or as a component within other phases. The majority, nine of the studies (64%), focused on the phases involving the extraction and production of materials, as well as the subsequent construction phase. In contrast, only three studies addressed the maintenance phase exclusively.

Despite the significance of the use phase according to previous research (e.g., Araújo et al. [26]), merely one study examined this phase, although in a superficial way, similarly to how the end-of-life phase was addressed. Interestingly, no clear temporal trend emerged over the years across the analyzed studies, whether in relation to life cycle phases or environmental indicators.

Table 1. Life cycle phases and environmental indicators examined in recent Brazilian studies.

Ref.	Year	Material[1]	Transportation of Materials	Construction	Use	Maintenance	End-of-Life	Energy Use	Greenhouse Gases	Acidification	Global Warming	Resource Depletion	Ozone Depletion	Human Toxicity	Respiratory Inorganics	Ionizing Radiation	Photochemical Ozone Formation	Eutrophication	Ecotoxicity	Land Use
						Pavement Life Cycle Phases ←	→				**Environmental Indicators** ←							→		
[42]	2017					x[2]		x		x	x			x			x	x	x	
[43]	2017	x	x			x[2]				x	x	x	x				x	x		
[44]	2017	x	x	x	x	x[2]		x			x							x		
[45]	2020	x	x	x						x	x			x				x	x	
[46]	2020	x	x	x				x	x											
[47]	2021	x	x	x						x	x		x					x	x	
[48]	2021	x	x	x				x	x											
[49]	2021	x	x					x		x	x									
[50]	2022	x	x	x				x	x											
[51]	2022	x	x	x						x	x	x	x	x			x	x	x	
[52]	2023					x[3]	x	x			x									
[53]	2023	x	x	x						x	x		x	x	x		x	x	x	
[54]	2023					x[2]				x	x			x			x	x	x	
[55]	2023	x	x	x				x	x											
Total		11	11	9	1	5	1	8	4	8	10	2	4	5	1	0	5	8	6	0

[1] Material extraction and production. [2] Involves materials extraction, production, transportation, and construction of maintenance activities. [3] Comprises only materials extraction, production, and transportation of maintenance activities.

4.2. Tools and Data Required for LCA Development

Other aspects worthy of comparison include the software, databases, and LCIA methods used to conduct these studies. These aspects are presented briefly in Table 2. Notably, the software that appears most frequently is SimaPro 9.5, which is mentioned in seven different cases, or 50% of the studies. Developed by the Dutch company Pré Sustainability, this software is among the most frequently used LCA software in the world. It was introduced in 1990 and is now in its ninth version. It includes more than twenty LCIA methods and more than nine inventory libraries (databases).

Table 2. Software, database, and LCIA method used in recent Brazilian studies.

Ref.	Software	Database	LCIA Method
[42]	GaBi; Pavement LCA	GaBi; USLCI; Pavement LCA	EDIP; TRACI
[43]	n/s	Ecoinvent 3.3; Votorantim Cimientos (2016) [56]	EN 15978 [57] EN 15804 [58]
[44]	SimaPro 8.0	Ecoinvent 3	IPCC
[45]	Umberto NXT LCA	Ecoinvent 3.4	CML
[46]	SimaPro	Ecoinvent; Stripple (2001) [59]; Farina et al. (2017) [60]; Edwards et al. (2017) [61]	n/s
[47]	openLCA 1.10	Ecoinvent 3; Fehrenbach et al. (2018) [62]	ReCiPe; IPCC; CML; EDIP; USEtox
[48]	Microsoft Office Excel	Ecoinvent 3.6; Eurobitume (2012) [63]; primary sources	n/s
[49]	SimaPro 9.0	Ecoinvent 3.5; Gschösser (2011) [64]; Gschösser et al. (2012) [65]; Siverio Lima et al. (2020) [66]	Ecoinvent; EN 15804
[50]	SimaPro	Ecoinvent	CML
[51]	SimaPro	Ecoinvent 3.4	CML
[52]	SimaPro 9.3	Ecoinvent 3.8	IPCC; Frischknecht et al. (2015) [67]; ReCiPe
[53]	openLCA	Federal LCA Commons	TRACI
[54]	openLCA 1.10	Ecoinvent 3	CML
[55]	SimaPro	Ecoinvent; Stripple (2001) [59]; Edwards et al. (2019) [61]	CML

The second most used software in Brazilian pavement LCA research is openLCA 2.0, cited in three studies. It is an open-source alternative equally suitable for professional LCA modeling. GreenDelta, an independent sustainability consulting firm in Germany, initiated this project in 2006, which focused on developing software for product LCA, identifying environmental consequences, and analyzing production costs. A notable observation is that all of the software listed in Table 2 originates from foreign sources, highlighting the urgent need for developing trusted Brazilian software and databases for future research projects.

The Ecoinvent 3.9 database was the primary database utilized in the examined studies, accounting for most of the references (86%, or 12 studies). Moreover, as illustrated in Table 2, a wide range of datasets utilized in this study were obtained from the academic literature, mostly because commercial databases lack complete and current Brazilian inventory libraries.

Regarding LCIA methods, the primary method utilized (in six of the studies) was developed by the Center of Environmental Science, Leiden University (Centrum voor Milieukunde Leiden—CML in Dutch). The method established by the Intergovernmental Panel on Climate Change (IPCC) claimed the second position. This method includes GHG metrics, making it suitable for calculating various impact assessment categories.

Furthermore, seven of the total analyzed studies exclusively considered a single method, five opted for using multiple LCIA methods, and the remaining two studies did not specify the applied LCIA method. In the multiple LCIA method scenario, authors arbitrarily assign particular LCIA methods to different environmental indicators to make the calculations. Moreover, there was no apparent association observed between the quantity of environmental indicators selected and the LCIA method chosen. Both choices were dependent on the subjective judgment of the authors. This highlights the LCA's inherent limitations and the persisting absence of consensus across studies.

4.3. Objects of Study in LCA Development

The specific pavement designs evaluated in each study were also analyzed to have a clear view of the gaps in this topic. Table 3 summarizes the functional units utilized, the different scenarios studied, and the construction activities considered in the inventory of the LCA.

Most studies (64%, which corresponds to 9 studies) employed length as their chosen functional unit, specifically 1 km of pavement. However, very few, if any, of these studies agree on the width of the pavement. In addition, two other studies opted for the area as their functional unit, specifically 1 m^2 of pavement, while a few considered volume or mass as their relevant metric.

Table 3. Functional units, scenarios studied, and construction activities considered in the inventory of recent Brazilian studies.

Ref.	Functional Unit	Scenarios Studied *	Construction Activities Considered in the Inventory
[42]	1 km pavement and 8.00 m wide	(1) HMA Structural Reinforcement (2) HMA Structural Reinforcement w/RAP	GaBi: n/s; USLCI: n/s Pavement LCA: (1) paving and milling; (2) hot in-place recycling and milling
[43]	1 m^3 concrete; 1 m^3 concrete/1 m^3 drained water	(1) PCC Pavement (2) PC Pavement	n/s
[44]	10 km pavement and 14.40 m wide	(1) HMA Pavement (2) HMA Pavement w/CTSB (3) PCC Pavement	(1) Paving, spraying, base rolling, and subgrade reinforcement rolling (2) Paving, spraying, base rolling, cemented sub-base, and subgrade reinforcement rolling (3) Paving, concrete base rolling, and sub-base rolling
[45]	1 km pavement and 10.70 m wide	(1) HMA Pavement (projected) (2) HMA Pavement (executed)	(1–2) Paving, spraying, base rolling, and sub-base rolling
[46]	1 m^2 pavement	(1) HMA Pavement w/SG base (2) HMA Pavement w/GGTC base (3) HMA Pavement w/RC base (4) HMA Pavement w/RMB base (5) HMA Pavement w/PMB base	n/s
[47]	1 km pavement and 7.20 m wide	(1) HMA Pavement (diesel) (2) HMA Pavement (biodiesel)	(1–2) Paving, spraying, base rolling, and sub-base rolling
[48]	1 km pavement and 23.50 m wide	(1) AC Range B dosage w/Limestone filler (2) AC Range B dosage w/Portland cement filler (3) AC Range C dosage w/Limestone filler (4) AC Range C dosage w/Portland cement filler	(1–4) Paving and spraying
[49]	1 kg asphalt mixture; 1 kg residue deposited in landfill	(1) AC w/Limestone filler (2) AC w/Dolomite filler (3) AC w/Red Mud filler (4) AC w/Fly Ash filler	n/a
[50]	1 km pavement and 3.60 m wide	(1) HMA Pavement w/LA subgrade (2) HMA Pavement w/LG' subgrade (3) HMA Pavement w/NA' subgrade	n/s
[51]	1 km pavement and 7.00 m wide	(1) SMA Pavement w/G base (2) SMA Pavement w/FA–CL base (3) SMA Pavement w/FA–CL–Salt base	(1–3) Paving, spraying, base rolling, and sub-base rolling
[52]	1 km pavement and 7.00 m wide	(1) BR: HMA Rehabilitation (2) BR: HMA Rehabilitation w/RAP (3) CH: HMA Rehabilitation (4) CH: HMA Rehabilitation w/RAP	n/a
[53]	1 t asphalt mixture; 1 m^2 pavement	(1) HMA Pavement (2) HMA Pavement w/RPET and w/o sub-base (3) HMA Pavement w/RPET	(1–3) Paving, base rolling, sub-base rolling, and subgrade grading

Table 3. *Cont.*

Ref.	Functional Unit	Scenarios Studied *	Construction Activities Considered in the Inventory
[54]	1 km pavement and varying widths	(1) Highway 1: HMA Structural Reinforcement (2) Highway 1: DR w/cement and HMA rubber (3) Highway 2: HMA Structural Reinforcement (4) Highway 2: DR w/cement and HMA rubber (5) Highway 2: Milling and HiMA (6) Highway 3: HMA Structural Reinforcement (7) Highway 3: DR w/cement and HMA rubber (8) Highway 3: Whitetopping	(1, 3, 6) Paving (2, 4, 7) Paving and deep recycling with cement (5) Paving and milling (8) PCC Paving
[55]	1 km pavement	(1) HMA Pavement w/LA subgrade (2) HMA Pavement w/LG' subgrade (3) HMA Pavement w/NA' subgrade (4) HMA Pavement w/NG' subgrade	(1–4) Paving, spraying, base rolling, sub-base rolling, and subgrade grading

* The identification numbers of the Scenarios Studied column are interconnected with the identification numbers of the Construction Activities considered in the Inventory column. Legend: Asphalt Concrete (AC); Brazil (BR); Switzerland (CH); Cement-Treated Sub-base (CTSB); Deep recycling (DR); Fly ash–Carbide Lime (FA–CL); Fly ash–Carbide Lime–Salt (FA–CL–Salt); Gravel (G); Graded Gravel Treated with Cement (GGTC); Highly Modified Asphalt Mixture (HiMA); Hot Mix Asphalt (HMA); Lateritic Sand Soil (LA); Lateritic Clay Soil (LG'); Non-lateritic Sandy Soil (NA'); Non-lateritic Clay Soil (NG'); Pervious Concrete (PC); Portland Cement Concrete (PCC); Asphalt Stabilized with a Polymer-modified Binder (PMB); Reclaimed Asphalt Pavement (RAP); Rolled Concrete (RC); Asphalt Stabilized with a Rubber-modified Binder (PMB); Recycled Post-consumer Polyethylene Terephthalate (RPET); Soil–gravel (SG); Stone Mastic Asphalt (SMA).

The type of pavement that gained the most attention in research was flexible pavements, which was examined in 93% of the studies. The fact that 99% of the pavements built in Brazil fall under this classification justifies this emphasis on using flexible pavements [68]. They typically consist of an asphalt surface course, a granular base course, and a granular sub-base course.

Within these studies of flexible pavement, two of them also compared semirigid and rigid pavement, and only one study conducted a comparative analysis only between semirigid and flexible pavement types. The use of semirigid pavements in Brazil has gained value over the years. These pavements maintain their flexible characteristics while increasing their stiffness. Semirigid pavements generally consist of a combination of an asphalt surface layer and a layer treated with hydraulic or bituminous binder to improve their stiffness. Out of all the 14 studies examined, only one exclusively focused on rigid pavements. They typically consist of a Portland cemented surface layer followed by a granular base. Their reputation comes from their superior endurance.

While most of the studies (9 out of 14) fell under this category, not all researchers focused solely on quantifying the impacts of new roadway construction. Some studies also directed their attention towards M&R, as well as the production and construction of only the asphalt surface course.

Figure 1 shows a comparison of the different types of surface, base, sub-base, and subgrade reinforcement layers that were studied in the chosen papers. This illustrates the frequency of occurrence of the different types of pavement materials utilized in each layer across various studies, offering insights into the existing gaps in the literature. There are instances in which multiple treatment types were evaluated within a single study; consequently, the total number of studies for each layer group may not necessarily equal fourteen.

There is a concentration of HMA research within the surface layer. This is unsurprising considering that HMA is the predominant technique used for asphalt paving in Brazil. Warm Mix Asphalt (WMA) was not focused on in the studies, indicative of its limited utilization in practical applications. Although ongoing research points toward a rising trend in adopting it for paving, this is primarily attributed to its requirement for lower manufacturing temperatures, resulting in reduced energy consumption and reduced emissions at the plant and project site.
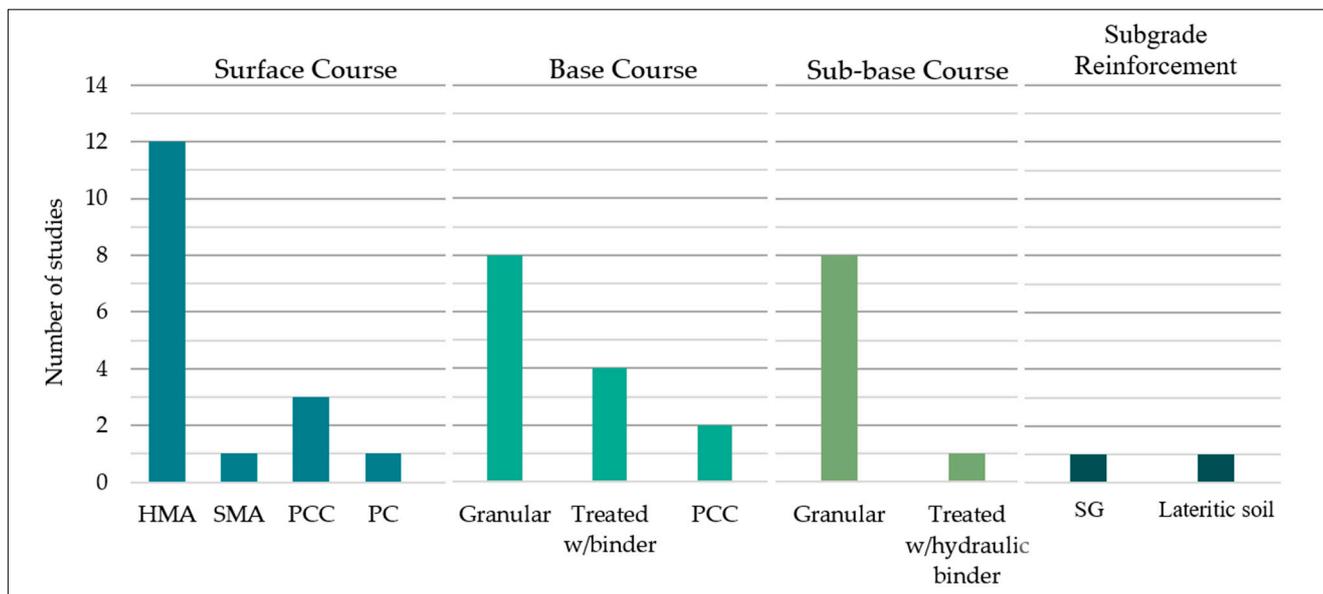
Figure 1. Frequency of appearance of surface course, base course, sub-base course, and subgrade reinforcement materials among the studies.

Surface treatments function as the interface between the existing pavement and the new structural reinforcement, preventing cracks in the underlying layers. Although these treatments did not receive special attention in the papers analyzed, they were occasionally covered in studies that centered on rehabilitation techniques.

One study from the collection examined two commonly employed rehabilitation interventions in Brazil. The first method is structural reinforcement, which requires milling a part of the existing surface course, applying a double bituminous surface treatment (DBST), and finishing with a new HMA layer with RAP. The second method, known as deep recycling, encompasses the milling of the entire existing surface course along with a portion of the base layer. This milled material is then treated with Portland cement and compacted before undergoing a similar process involving DBST and a fresh layer of HMA. The comprehensive comparison of these M&R techniques, along with other ones, is an interesting contribution by Luvizo et al. [54]. Their findings indicate that structural reinforcement has the most significant impact over a 30-year period, whereas deep recycling results in a notable 40–48% reduction in emissions.

Granular base courses have been the subject of most research; however, a number of studies have investigated base treatments involving hydraulic and bituminous binders. This is a usual technique in Brazilian base construction, in which Portland cement is the most popular binder option.

When it comes to subgrade treatments, the practice may not be very necessary due to the fact that Brazilian subgrades typically consist of high-strength capacity and California Bearing Ratio (CBR) values. They often comprise lateritic soil, typical of subtropical regions. In cases where the subgrade does exhibit lower resistance values, one approach that is employed in Brazil involves adding a subgrade reinforcement layer on top of the subgrade. When inserted, this layer usually comprises soil–gravel materials, and as seen in Figure 1, few studies have explored its incorporation and its materials' variations.

Table 3 also includes the construction activities considered in the inventory. The practice of road construction involves numerous kinds of activities that, when combined, result in the construction of pavements we use daily. In order to simplify these activities, they have been arranged into several groupings: paving, milling, spraying, recycling, base rolling, sub-base rolling, subgrade reinforcement rolling, and subgrade grading. Among these processes, paving emerged as the most frequent activity, appearing in 64% of the studies (9 instances). The frequency of this occurrence was greater than the occurrences of

base and sub-base rolling, which were each reported in six studies. The variation is mainly attributed to the fact that not all case studies covered all the pavement layers of construction; some focused solely on the surface course, whereas others emphasized M&R techniques.

The resulting emissions from these activities were primarily quantified in terms of energy consumption or fuel consumption in liters. By considering the hours or kilometers involved, researchers were able to estimate the volume of emissions generated through the utilization of the equipment required to execute these processes. A significant proportion of the analyzed studies (35%) did not include specifications for any construction activities. This is a considerable fraction that should be addressed in subsequent investigations.

4.4. Inventory Analysis in LCA Development

The implementation of a database suitable for the geographical region stated within the study's scope is another essential aspect that contributes to the accuracy of the LCA results. In this regard, the materials used and the regions where the processes related to these materials were carried out have been identified for the inventory of the studies under analysis. These data, coupled with a more detailed examination of material transportation, are summarized in Table 4.

Table 4. Materials and segments of transportation considered in the inventory of recent Brazilian studies.

Ref.	Pavement Materials Considered in the Inventory (Region) [1]	Transportation Segments [2]			
		Supplier to Site	Supplier to Plant	Plant to Site	Site to Landfill
[42]	GaBi: asphalt (BR) and gravel (DE) USLCI: asphalt (US) and limestone (US) Pavement LCA: HMA	x		x	
[43]	Portland cement (BR), sand, gravel, and plasticizer additive			x	
[44]	Fuel oil, PAC 50/70, PAC 65/90 SBS polymer-modified, CM 30 priming, RR 1C bond coat, Portland cement CP II-32, sand, filler, polyethylene limiter strip, polymerized asphalt sealant, steel CA-25, steel CA-50, and gravel	x	x	x	x
[45]	Basalt aggregate (RoW) and asphalt (RoW)	x	x	x	x
[46]	PAC 30/45, PAC 65/90 polymer-modified, Portland cement CP II–32, sand, limestone, gravel, and PAC 50/70 15% rubber-modified	x	x	x	
[47]	Sand (BR), gravel (BR), and asphalt (GLO)	x	x	x	
[48]	Gravel (BR), sand (BR), crushed stone powder (BR), cement (BR), limestone powder (CA), SBS polymer-modified PAC, CM 30 priming, and RR 1C bond coat		x	x	
[49]	Sand (GLO), gravel (RoW), asphalt (GLO), limestone (RoW), dolomite (RoW), red mud (GLO), and fly ash (RoW) fillers		x		
[50]	Fuel oil, PAC 30/45, sand, limestone, and gravel	x	x	x	
[51]	Asphalt, gravel, fly ash, carbide lime, and salt	x		x	
[52]	BR: gravel (BR), asphalt (BR), and polymer modifier CH: gravel (CH), asphalt (CH), and polymer modifier		x		
[53]	Gravel (BR), rock filler, RPET-micronized (US), RPET flakes (US), and asphalt (RNA)	x	x	x	
[54]	Asphalt, asphalt emulsion, Portland cement, gravel, macadam, soil, and limestone	x	x	x	
[55]	Fuel oil, PAC 30/45, sand, limestone, and gravel	x	x	x	

[1] Only the regions referenced in the studies have been incorporated. [2] Segments of Materials' Transportation considered in the Inventory. Legend: Germany (DE); Global (GLO); Petroleum Asphalt Cement (PAC); Northern America (RNA); Rest of the World (RoW); United States (US).

Despite the fact that every study focuses on Brazil, the regions where material processing was conducted differ from the study's geography. Utilizing global data is also acceptable given the limitations associated with data accessibility. Within six studies, at

least one material process was located within the geographical boundaries of Brazil; two studies relied on global data; and six studies did not specify the geographical locations of the materials' processes.

LCA research conducted in Brazil does not adequately support the claim that the use of recycled materials, such as post-consumer plastic and tire rubber, and WMA techniques in the construction of pavements is environmentally sustainable. The only existing study in this specific area was conducted by Osorto et al. [53]. A comparative analysis was performed between a traditional HMA pavement and one that integrated RPET via the dry process. The findings revealed a significant 38% reduction in overall environmental impacts, favoring the environmentally sustainable pavement alternative.

The last column in Table 4 presents an in-depth examination of the transportation phase of the raw materials. Around 43% of the studies, specifically 6 out of 14, examined three segments: supplier to site, supplier to plant, and plant to site. Within the 14 studies examined, the transportation segment "plant to site" received the most interest, closely followed by the "supplier to plant" segment. The latter refers to the transportation of materials from the primary supplier of raw materials to the asphalt plant, where subsequent processing takes place to manufacture the surface course mix.

Attempts were made to evaluate and contrast the transportation distances applied to different materials within each study. First, only 7 of the 14 papers made reference to the distance assumptions, leaving half of the studies without this information. Furthermore, after careful analysis of the given distances, no apparent correlations or patterns were observed regarding the magnitude of these distance assumptions. They demonstrated significant variations from one study to another. Asphalt, a material known for its significant contribution to energy consumption in asphalt mixture construction [49], demonstrated varying transportation distances in the range of 98 km [44] and 750 km [53], as reported in separate studies. The broad distances can be attributed largely to the vast territorial expanse of the country.

When studying sustainable production and manufacturing processes, especially those reliant on power, feedstock energy needs to be considered. Feedstock is defined as any renewable, biological material that can be used directly as a fuel or converted into another form of fuel or energy product [69]. In the LCA of pavements, this consideration is of great importance due to the reliance on bitumen and fuel. Half of the examined studies considered or adapted their energy supply to align with Brazil's energy matrix. This has a substantial effect on the final results due to Brazil's vast use of renewable energy sources. As of 2022, the country's energy matrix comprised 61.9% hydraulic, 11.8% wind, 8.0% biomass, 6.1% natural gas, 4.4% solar, and 7.8% from other sources [70].

Not every paper provided detailed information regarding the source or methodology used to measure energy consumption. However, in several research projects, the quantity of fuel consumed served as a metric to establish a relationship between energy consumption and the environmental impacts resulting from the burning of fossil fuels. This was particularly common in cases involving machinery and equipment during the construction and transportation phases, as observed in 9 out of the 14 studies evaluated.

It was noted that diesel was the most frequently used fuel in the inventories. For instance, Grael et al. [47] investigated an alternative scenario in which biodiesel replaced diesel for the transportation of raw materials. Surprisingly, this substitution did not prove to be beneficial, as the use of biodiesel resulted in a 29% increase in global warming compared to the diesel scenario. This could be attributed to the production of soybean oil, which serves as a raw material in biodiesel production in Brazil. It appears that emissions from diesel fuel use in machinery during land conversion and transformation for soy plantations played a significant role in this outcome. As a result, it is also essential to consider the sustainability of feedstock energy sources.

4.5. Results after LCA Development

In addition to the qualitative examination discussed previously, it was considered necessary to make a quantitative comparison between the results of the studied scenarios in each investigation (see Figure 2). Given the inherent limitations of comparing LCA case studies, specific papers with similar scopes were chosen. The selection criteria were established based on the earlier evaluation of the frequency of the addressed topics. Papers were filtered based on their coverage of new road construction and on the material extraction and production, material transportation, and construction phases. In addition, the filtered papers adhered to a minimum performance criterion of 30% cracked area at the end of the pavement's life span (applied to [46,50,55]). Then, as numerous papers utilized a functional unit of 1 km of pavement, though with varying road widths, a unit normalization process was carried out. Through mathematical operations, all results were expressed in terms of 1 m^2 of pavement. The environmental indicator used for this comparison is global warming in kilograms of CO_2 equivalent. This choice was made due to its prominence as the most examined factor among the research studies.
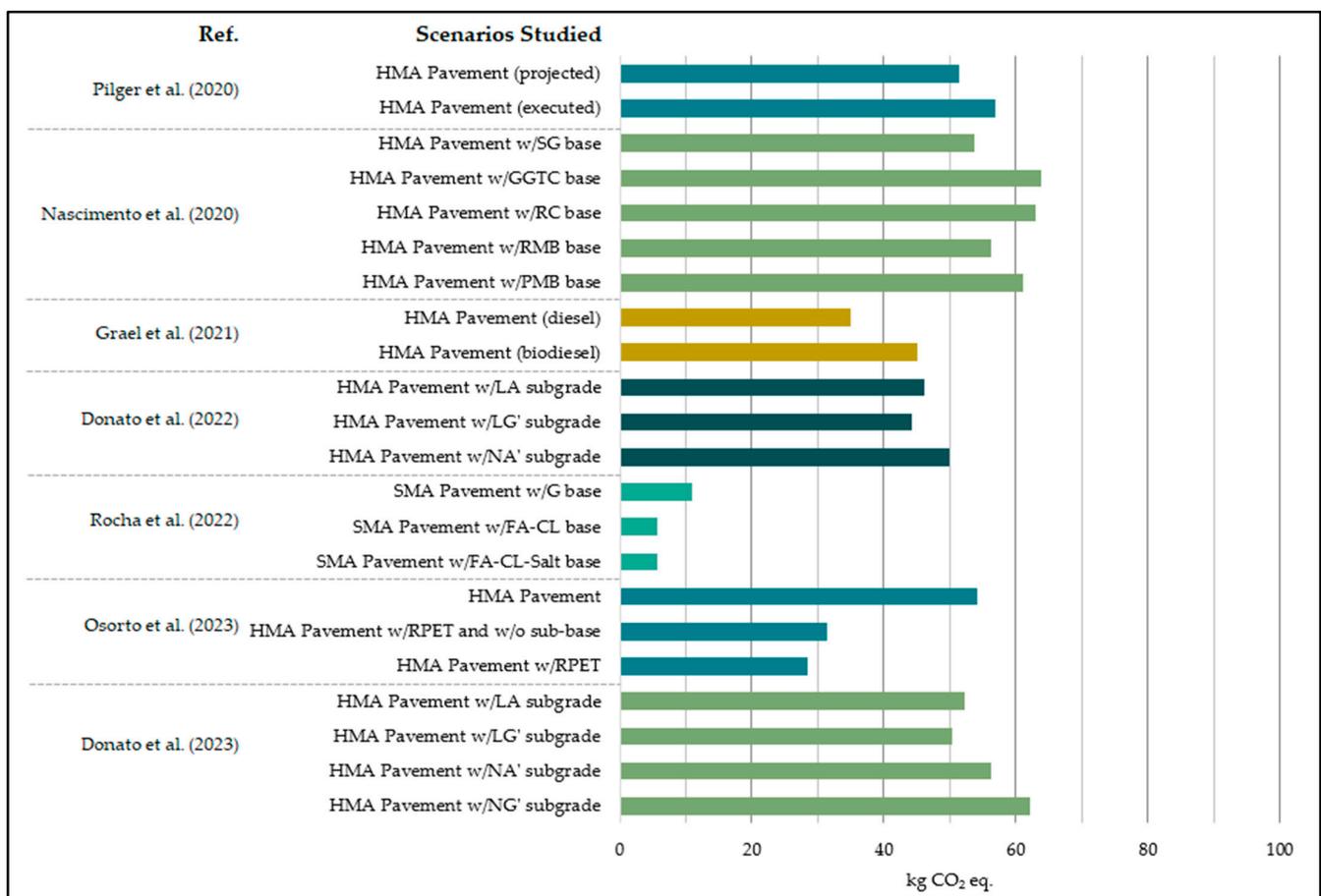

Figure 2. Quantitative comparison of kg CO_2 eq per m^2 of pavement in recent Brazilian studies [45–47,50–52,54].

The scenarios showing the lowest emissions were those using SMA pavement [51]. These indicated 10.91 kg of CO_2 eq per square meter for the scenario with a gravel base and 5.79 kg of CO_2 eq per square meter for the scenarios with an FA–CL base and an FA–CL–Salt base. The two scenarios with the highest emissions were HMA Pavement with GGTC base and HMA Pavement with RC base, with reported emissions of 63.90 kg of CO_2 equivalent per square meter and 63.00 kg of CO_2 equivalent per square meter, respectively [46]. This emission difference can be attributed to variations in the design criteria of the road

surfaces. Specifically, scenarios using SMA utilized a 5.0 cm thick surface course. In contrast, scenarios with the highest emissions had asphalt thicknesses of 20.5 cm and 18.0 cm, respectively, and incorporated Portland cement in the base construction. Notably, Portland cement's energy-intensive manufacturing process contributes significantly to negative environmental impacts in road construction.

When analyzing only conventional HMA pavements with granular bases and sub-bases, interestingly, there was a notable proximity in the results. The average global warming emissions were found to be 50.59 kg of CO_2 eq per square meter of pavement, with a standard deviation of 6.86 kg of CO_2 eq. What was also intriguing was that, in the quantitative comparison, every study analyzed, except Osorto et al. [53], had used the Ecoinvent database to some extent. Furthermore, five out of the seven case studies commonly employed the CML method for LCIA, and four out of the seven utilized the SimaPro software. This could suggest the existence of a certain level of reproducibility, but given the short list of papers, more research is needed to reach a solid verdict.

One of the significant findings from pavement LCA studies in Brazil is that the use of recycled materials, such as reclaimed asphalt pavement and asphalt, can significantly reduce the environmental impacts of pavement construction and maintenance [42,52]. The analysis further reveals that the material production and extraction phases are the most significant sources of environmental impacts [42,44,47]. This phase is characterized by substantial emissions of GHG as a result of fuel consumption, specifically gases and heavy oils [51,52]. Nonetheless, some inconsistencies exist in the material transportation phase. Some studies suggest that this stage has little environmental impact [43], while others argue that it is one of the most polluting [47].

The location where pavement is constructed presents another important aspect of pavement LCAs. Regional differences in factors such as materials, machinery, climate, topography, and traffic conditions can all affect the environmental impact of a pavement system. Pavement systems built in different regions of Brazil, such as the Amazon region and the south, may have varying environmental impacts, for example, because of the extraction process of sand and pebbles [48]. However, recent research has shown that construction practices and technologies employed during the building phase have a greater influence on the LCA results than the region itself [52].

In cases where pavement infrastructure is constructed on top of lateritic soil, a common occurrence in subtropical regions such as Brazil, LCA indicates reduced environmental impacts compared to when it is built on non-lateritic soils [50,55]. This is primarily attributed to the inherited characteristics of lateritic soils, which typically feature higher CBR values and lower expansion rates [71]. As a result, the required thickness of the upper layers decreases, leading to a reduction in material quantity and, consequently, lower emissions.

Overall, LCA studies on pavements in Brazil contribute to developing sustainable pavement design and construction practices. These studies have focused on reducing environmental impacts while maintaining good pavement performance; even integrating social [50] and cost considerations [50].

5. Conclusions

This paper provides a comprehensive overview of the application of LCA in evaluating the sustainability implications of transportation infrastructure in Brazil. It summarizes key findings and gaps identified in case studies related to pavement LCA. The paper also emphasizes the potential of integrating the IRI as a performance criterion to enhance pavement sustainability. Research indicates that the IRI can complement LCA results, achieving a balance between durability and sustainability. Smoother pavements offer advantages such as reduced vehicle wear and tear, decreased maintenance needs, and lower fuel consumption, contributing to long-term economic savings. However, developing a prediction model that considers factors such as pavement structure, location, climate, and traffic conditions is essential when working with the IRI.

The study examines fourteen quantitative LCA studies conducted in Brazil, collected through extensive bibliographic research across various platforms, including their scopes, tools, databases, inventories, results, and discussions. The findings highlight the inherent limitations of the LCA methodology, particularly its reliance on secondary data. Ecoinvent, SimaPro, and CML were the most commonly used databases, software, and LCIA methods, respectively. Even when adopting secondary databases and foreign software, maintaining regional relevance by using processes specific to Brazil and matching the country's energy matrix is imperative. LCAs often require assumptions and adjustments to align inputs with selected databases. Future studies should focus more on obtaining representative Brazilian data.

Despite variability and incompleteness in the studied life cycle phases and environmental indicators, the paper makes a quantitative comparison by filtering studies with similar scopes and analyzing the ones with matching life cycle phases and the global warming indicator. Notably, most of these studies shared the same database and LCIA method. HMA pavements with granular bases and sub-bases emitted an average of 50.59 kg of CO_2 eq per square meter of pavement. Regarding the most environmentally impactful life cycle phase, no conclusion can be drawn as none of the studies encompassed all phases of the pavement life cycle.

While it may be premature to provide best practice policies or recommendations on materials and maintenance strategies due to the limited number of available papers, the research suggests that future sustainability-focused projects could consider integrating recycled materials into the surface course mixture and employing high-strength capacity materials in subgrade and pavement layers. However, the most important approach for a sustainable life span with less frequent maintenance is ensuring good-quality materials and construction finishes to ensure superior performance.

To provide a comprehensive view of environmental impact quantification and actionable guidance, standardizing functional units, expanding system boundaries, and improving data quality and reliability are essential. LCA studies have played a crucial role in promoting the sustainable development of pavements. Continued research in Brazil is vital to enhance its effectiveness and contribute to sustainability goals. To address the gaps identified in this paper, future research should incorporate inputs and models from various scientific fields, summarized in a literature overview, to establish a comprehensive conceptual framework. Additionally, conducting a case study in Brazil covering materials, construction, and use phases while integrating the IRI as a performance indicator and considering variations in construction materials and thickness layers would provide a more comprehensive understanding of sustainability implications in pavement construction and usage.

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References

1. CNT. *Anuário CNT Do Transporte 2022*; CNT: Brasília, Brazil, 2022.

2. Potenza, R.; Quintana, G.; Cardoso, A.; Tsai, D.; dos Cremer, M.S.; Barcellos, E.; Silva, F.; Carvalho, K.; Coluna, I.; Shimbo, J.; et al. *Análise Das Emissões de Gases de Efeito Estufa e Suas Implicações Para as Metas Climáticas Do Brasil 1970–2021*; SEEG: Brasília, Brazil, 2023.

3. *ABNT NBR ISO 14040*; Gestão Ambiental–Avaliação Do Ciclo de Vida–Princípios e Estrutura. Associação Brasileira de Normas Técnicas: Rio de Janeiro, Brazil, 2009.

4. Horne, R.; Grant, T.; Verghese, K. *Life Cycle Assessment: Principles, Practice, and Prospects*; CSIRO Publishing: Clayton, Australia, 2009; ISBN 9780643097964.

5. Willers, C.D.; Rodrigues, L.B.; Silva, C.A. da Avaliação Do Ciclo de Vida No Brasil: Uma Investigação Nas Principais Bases Científicas Nacionais. *Production* **2013**, *23*, 436–447. [CrossRef]

6. Santero, N.J.; Masanet, E.; Horvath, A. Life-Cycle Assessment of Pavements. Part I: Critical Review. *Resour. Conserv. Recycl.* **2011**, *55*, 801–809. [CrossRef]

7. *ABNT NBR ISO 14044*; Gestão Ambiental—Avaliação Do Ciclo de Vida—Requisitos e Orientações. Associação Brasileira de Normas Técnicas: Rio de Janeiro, Brazil, 2009.

8. Curran, M.A. Strengths and Limitations of Life Cycle Assessment. In *Background and Future Prospects in Life Cycle Assessment*; Springer: Dordrecht, The Netherlands, 2014; pp. 189–206.

9. Huang, Y.; Bird, R.; Heidrich, O. Development of a Life Cycle Assessment Tool for Construction and Maintenance of Asphalt Pavements. *J. Clean. Prod.* **2009**, *17*, 283–296. [CrossRef]

10. Reap, J.; Roman, F.; Duncan, S.; Bras, B. A Survey of Unresolved Problems in Life Cycle Assessment Part 1: Goal and Scope and Inventory Analysis. *Int. J. Life Cycle Assess.* **2008**, *13*, 290–300. [CrossRef]

11. Azarijafari, H.; Yahia, A.; Amor, M. Ben Life Cycle Assessment of Pavements: Reviewing Research Challenges and Opportunities. *J. Clean. Prod.* **2016**, *112*, 2187–2197. [CrossRef]

12. Finnveden, G.; Hauschild, M.Z.; Ekvall, T.; Guinée, J.; Heijungs, R.; Hellweg, S.; Koehler, A.; Pennington, D.; Suh, S. Recent Developments in Life Cycle Assessment. *J. Environ. Manag.* **2009**, *91*, 1–21. [CrossRef]

13. Du, C.; Kulay, L.; Cavalett, O.; Dias, L.; Freire, F. Life Cycle Assessment Addressing Health Effects of Particulate Matter of Mechanical versus Manual Sugarcane Harvesting in Brazil. *Int. J. Life Cycle Assess.* **2018**, *23*, 787–799. [CrossRef]

14. Restrepo, Á.; Bazzo, E.; Miyake, R. A Life Cycle Assessment of the Brazilian Coal Used for Electric Power Generation. *J. Clean. Prod.* **2015**, *92*, 179–186. [CrossRef]

15. Rousset, P.; Caldeira-Pires, A.; Sablowski, A.; Rodrigues, T. LCA of Eucalyptus Wood Charcoal Briquettes. *J. Clean. Prod.* **2011**, *19*, 1647–1653. [CrossRef]

16. Oberle, B.; Bringezu, S.; Hatfield-Dodds, S.; Hellweg, S.; Schandl, H.; Clement, J. *Global Resources Outlook: 2019*; International Resource Panel: Paris, France, 2019.

17. Rodrigue, J.P.; Comtois, C.; Slack, B. *The Geography of Transport Systems*; Taylor and Francis: New York, NY, USA, 2006; ISBN 9781317210108.

18. Ibrahim, S.H.; Ibrahim, N.I.A.; Wahid, J.; Goh, N.A.; Koesmeri, D.R.A.; Nawi, M.N.M. The Impact of Road Pavement on Urban Heat Island (UHI) Phenomenon. *Int. J. Technol.* **2018**, *9*, 1597–1608. [CrossRef]

19. Chong, D.; Wang, Y. Impacts of Flexible Pavement Design and Management Decisions on Life Cycle Energy Consumption and Carbon Footprint. *Int. J. Life Cycle Assess.* **2017**, *22*, 952–971. [CrossRef]

20. Yuan, X.; Tang, Y.; Li, Y.; Wang, Q.; Zuo, J.; Song, Z. Environmental and Economic Impacts Assessment of Concrete Pavement Brick and Permeable Brick Production Process—A Case Study in China. *J. Clean. Prod.* **2018**, *171*, 198–208. [CrossRef]

21. Chowdhury, R.; Apul, D.; Fry, T. A Life Cycle Based Environmental Impacts Assessment of Construction Materials Used in Road Construction. *Resour. Conserv. Recycl.* **2010**, *54*, 250–255. [CrossRef]

22. Santero, N.J.; Masanet, E.; Horvath, A. Life-Cycle Assessment of Pavements Part II: Filling the Research Gaps. *Resour. Conserv. Recycl.* **2011**, *55*, 810–818. [CrossRef]

23. Barandica, J.M.; Fernández-Sánchez, G.; Berzosa, Á.; Delgado, J.A.; Acosta, F.J. Applying Life Cycle Thinking to Reduce Greenhouse Gas Emissions from Road Projects. *J. Clean. Prod.* **2013**, *57*, 79–91. [CrossRef]

24. Inti, S.; Martin, S.A.; Tandon, V. Necessity of Including Maintenance Traffic Delay Emissions in Life Cycle Assessment of Pavements. *Procedia Eng.* **2016**, *145*, 972–979. [CrossRef]

25. Akbarian, M.; Ulm, F.J.; Xu, X.; Kirchain, R.; Gregory, J.; Louhghalam, A.; Mack, J. Overview of Pavement Life Cycle Assessment Use Phase Research at the MIT Concrete Sustainability Hub. In *Airfield and Highway Pavements 2019*; American Society of Civil Engineers: Reston, VI, USA, 2019; pp. 193–206, ISBN 9780784482476.

26. Araújo, J.P.C.; Oliveira, J.R.; Silva, H.M. The Importance of the Use Phase on the LCA of Environmentally Friendly Solutions for Asphalt Road Pavements. *Transp. Res. D Transp. Environ.* **2014**, *32*, 97–110. [CrossRef]

27. Kucukvar, M.; Noori, M.; Gokhan, E.; Tatari, O. Stochastic Decision Modeling for Sustainable Pavement Designs. *Int. J. Life Cycle Assess.* **2014**, *19*, 1185–1199. [CrossRef]

28. Sun, L. *Structural Behavior of Asphalt Pavements: Intergrated Analysis and Design of Conventional and Heavy Duty Asphalt Pavement*; Butterworth-Heinemann: Oxford, UK, 2016; ISBN 978-0-12-849908-5.

29. Shah, Y.U.; Jain, S.; Tiwari, D.; Jain, M. Development of Overall Pavement Condition Index for Urban Road Network. *Procedia Soc. Behav. Sci.* **2013**, *104*, 332–341. [CrossRef]

30. FHWA. *Highway Performance Monitoring System Field Manual*; FHWA: Washington, DC, USA, 2016.

31. Greene, S.; Akbarian, M.; Ulm, F.-J.; Gregory, J. Pavement Roughness and Fuel Consumption. In *Concrete Sustainability Hub*; Massachusetts Institute of Technology: Cambridge, MA, USA, 2013.
32. Santos, J.; Bryce, J.; Flintsch, G.; Ferreira, A.; Diefenderfer, B. A Life Cycle Assessment of In-Place Recycling and Conventional Pavement Construction and Maintenance Practices. *Struct. Infrastruct. Eng.* **2015**, *11*, 1199–1217. [CrossRef]
33. Akbarian, M. Model Based Pavement-Vehicle Interaction Simulation for Life Cycle Assessment of Pavements. Ph.D. Thesis, Massachusetts Institute of Technology, Cambridge, MA, USA, 2012.
34. Xu, X.; Akbarian, M.; Gregory, J.; Kirchain, R. Role of the Use Phase and Pavement-Vehicle Interaction in Comparative Pavement Life Cycle Assessment as a Function of Context. *J. Clean. Prod.* **2019**, *230*, 1156–1164. [CrossRef]
35. Liu, X.; Al-Qadi, I. Integrated Vehicle–Tire–Pavement Approach for Determining Pavement Structure–Induced Rolling Resistance under Dynamic Loading. *Transp. Res. Rec.* **2022**, *2676*, 398–409. [CrossRef]
36. Akbarian, M.; Moeini-Ardakani, S.S.; Ulm, F.J.; Nazzal, M. Mechanistic Approach to Pavement-Vehicle Interaction and Its Impact on Life-Cycle Assessment. *Transp. Res. Rec.* **2012**, *2306*, 171–179. [CrossRef]
37. Estaji, M.; Coleri, E.; Harvey, J.T.; Butt, A.A. Predicting Excess Vehicle Fuel Use Due to Pavement Structural Response Using Field Test Results and Finite Element Modelling. *Int. J. Pav. Eng.* **2021**, *22*, 973–983. [CrossRef]
38. Yang, R.; Kang, S.; Ozer, H.; Al-Qadi, I.L. Environmental and Economic Analyses of Recycled Asphalt Concrete Mixtures Based on Material Production and Potential Performance. *Resour. Conserv. Recycl.* **2015**, *104*, 141–151. [CrossRef]
39. Zhao, Z.; Guo, Z. Prediction of Asphalt Pavement International Roughness Index (IRI) by Combined Approach of Empirical Regression and Markov. In Proceedings of the ICTE 2013: Safety, Speediness, Intelligence, Low-Carbon, Innovation, Chengdu, China, 19–20 October 2013; pp. 2103–2113.
40. Kargah-Ostadi, N.; Stoffels, S.M.; Tabatabaee, N. Network-Level Pavement Roughness Prediction Model for Rehabilitation Recommendations. *Transp. Res. Rec.* **2010**, *2155*, 124–133. [CrossRef]
41. Wolf, M.; Chomkhamsri, K.; Brandao, M.; Pant, R.; Ardente, F.; Pennington, D.; Manfredi, S.; De Camillis, C.; Goralczyk, M. *International Reference Life Cycle Data System (ILCD) Handbook—General Guide for Life Cycle Assessment—Detailed Guidance*; EUR 24708 EN; Publications Office of the European Union: Luxembourg, 2010; ISBN 9789279190926.
42. Savietto, J.P. Análise de Impactos Ambientais Da Restauração de Pavimentos Asfálticos Pela Avaliação Do Ciclo de Vida. Master's Thesis, Universidade de São Paulo, São Carlos, Brazil, 2017.
43. Caldas, L.R.; Lins, D.N.; Sposto, R.M. Avaliação Do Ciclo de Vida de Pavimento de Concreto Drenante Considerando Diferentes Unidades Funcionais. *Mix. Sustentável* **2017**, *3*, 14–23. [CrossRef]
44. Souza, L.d.P. Uso Integrado Das Ferramentas de Análise Do Ciclo de Vida e de Análise Do Custo Do Ciclo de Vida Em Pavimentação. Master's Thesis, Universidade de São Paulo, São Paulo, Brazil, 2017.
45. Pilger, J.D.; Machado, Ê.L.; de Assis Lawisch-Rodriguez, A.; Zappe, A.L.; Rodriguez-Lopez, D.A. Environmental Impacts and Cost Overrun Derived from Adjustments of a Road Construction Project Setting. *J. Clean. Prod.* **2020**, *256*, 120731. [CrossRef]
46. Nascimento, F.; Gouveia, B.; Dias, F.; Ribeiro, F.; Silva, M.A. A Method to Select a Road Pavement Structure with Life Cycle Assessment. *J. Clean. Prod.* **2020**, *271*, 122210. [CrossRef]
47. Grael, P.F.F.; Oliveira, L.S.B.L.; Oliveira, D.S.B.L.; Bezerra, B.S. Life Cycle Inventory and Impact Assessment for an Asphalt Pavement Road Construction—A Case Study in Brazil. *Int. J. Life Cycle Assess.* **2021**, *26*, 402–416. [CrossRef]
48. Da Silva, I.N.; Maués, L.M.F. Inventory of Sand and Pebble Production for Use in Hot Mix Asphalt: A Case Study in Brazil. *J. Clean. Prod.* **2021**, *294*, 126271. [CrossRef]
49. Lima, M.S.S.; Hajibabaei, M.; Thives, L.P.; Haritonovs, V.; Buttgereit, A.; Queiroz, C.; Gschösser, F. Environmental Potentials of Asphalt Mixtures Fabricated with Red Mud and Fly Ash. *Road Mater. Pav. Design* **2021**, *22*, S690–S701. [CrossRef]
50. Donato, M.; Gouveia, B.G.; de Medeiros, A.S.; da Silva, M.A.V.; Oda, S. Mechanical Analysis of Subgrades of Road Pavements in Life Cycle Assessment. *Civ. Eng. J.* **2022**, *8*, 1492–1506. [CrossRef]
51. da Rocha, C.G.; Saldanha, R.B.; de Araújo, M.T.; Consoli, N.C. Social and Environmental Assessments of Eco-Friendly Pavement Alternatives. *Constr. Build. Mater.* **2022**, *325*, 126736. [CrossRef]
52. Mascarenhas, Z.M.; Piao, Z.; Vasconcelos, K.L.; Poulikakos, L.D.; Bernucci, L.L. Comparative Environmental Performance of Pavement Structures Considering Recycled Materials and Regional Differences. *Sci. Total Environ.* **2023**, *858*, 159862. [CrossRef] [PubMed]
53. Osorto, M.R.R.; Casagrande, M.D.T. Environmental Impact Comparison Analysis between a Traditional Hot Mixed Asphalt (HMA) and with the Addition of Recycled Post-Consumer Polyethylene Terephthalate (RPET) through the Life Cycle Assessment (LCA) Methodology. *Sustainability* **2023**, *15*, 1102. [CrossRef]
54. Luvizão, G.; Trichês, G. Case Study on Life Cycle Assessment Applied to Road Restoration Methods. *Sustainability* **2023**, *15*, 6679. [CrossRef]
55. Donato, M.; Gouveia, B.G.; de Garcia, B.T.G.; da Silva, M.A.V. Verificação de Método de Seleção de Pavimentos Rodoviários a Partir de Critérios de Eficiência. In Proceedings of the Anais do 36° Congresso de Pesquisa e Ensino em Transportes, Fortaleza, Brazil, 8–12 November 2023.
56. Votorantim Cimentos. *Cements CP II E 40, CP III-40 RS and CP V-ARI (Bulk Form)*; Votorantim Cimentos: São Paulo, Brazil, 2016.
57. *BS EN 15978:2011*; Sustainability of Construction Works. Assessment of Environmental Performance of Buildings. Calculation Method. European Standards: Brussels, Belgium, 2011.

58. *BS EN 15804*; Sustainability of Construction Works—Environmental Product Declarations—Core Rules for the Product Category of Construction Products. European Standards: Brussels, Belgium, 2012.

59. Stripple, H. *Life Cycle Assessment of Road. A Pilot Study for Inventory Analysis*; IVL Swedish Environmental Research Institute: Stockholm, Sweden, 2001.

60. Farina, A.; Zanetti, M.C.; Santagata, E.; Blengini, G.A. Life Cycle Assessment Applied to Bituminous Mixtures Containing Recycled Materials: Crumb Rubber and Reclaimed Asphalt Pavement. *Resour. Conserv. Recycl.* **2017**, *117*, 204–212. [CrossRef]

61. Edwards, R.; Padella, M.; Giuntoli, J.; Koeble, R.; O'Connell, A.; Bulgheroni, C.; Marelli, L. *Definition of Input Data to Assess GHG Default Emissions from Biofuels in EU Legislation*; European Union: Brussels, Belgium, 2017.

62. Fehrenbach, H.; Liebich, A.; Abdalla, N.; Biemann, K.; Fröhlich, T.; Simon, B. *Life Cycle Inventories of Petroleum Refinery Operation*; Ecoinvent Association: Zürich, Switzerland, 2018.

63. Eurobitume. *Life Cycle Inventory: Bitumen*; Eurobitume: Brussels, Belgium, 2012.

64. Gschösser, F. Environmental Assessment of Road Constructions: Life Cycle Assessment of Swiss Road Pavements and an Accompanying Analysis of Construction and Maintenance Costs. Ph.D. Thesis, ETH Zürich, Zürich, Switzerland, 2011.

65. Gschösser, F.; Wallbaum, H.; Boesch, M.E. Life-Cycle Assessment of the Production of Swiss Road Materials. *J. Mater. Civ. Eng.* **2012**, *24*, 168–176. [CrossRef]

66. Siverio Lima, M.S.; Hajibabaei, M.; Hesarkazzazi, S.; Sitzenfrei, R.; Buttgereit, A.; Queiroz, C.; Tautschnig, A.; Gschösser, F. Environmental Potentials of Asphalt Materials Applied to Urban Roads: Case Study of the City of Münster. *Sustainability* **2020**, *12*, 6113. [CrossRef]

67. Frischknecht, R.; Wyss, F.; Büsser Knöpfel, S.; Lützkendorf, T.; Balouktsi, M. Cumulative Energy Demand in LCA: The Energy Harvested Approach. *Int. J. Life Cycle Assess.* **2015**, *20*, 957–969. [CrossRef]

68. CNT. *Pesquisa CNT de Rodovias 2022*; CNT: Brasília, Brazil, 2022.

69. Kataki, R.; Chutia, R.S.; Mishra, M.; Bordoloi, N.; Saikia, R.; Bhaskar, T. Feedstock Suitability for Thermochemical Processes. In *Recent Advances in Thermochemical Conversion of Biomass*; Elsevier: Amsterdam, The Netherlands, 2015; pp. 31–74, ISBN 9780444632906.

70. EPE. *Balanço Energético Nacional (BEN) 2023: Ano Base 2022*; EPE: Brasília, Brazil, 2023.

71. Nogami, J.S. Características Dos Solos Tropicais. In *Reunião Aberta da Indústria de Solo Cal: O Uso da Cal na Engenharia Civil*; EPUSP/Abpc: São Paulo, Brazil, 1985; pp. 47–55.