

## Comprehensive review of life cycle assessment methodologies for passenger vehicles

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**Abstract:** *Purpose:* This paper aims to advance knowledge in the methodology of environmental life cycle assessment (LCA) for vehicles and to discern potential environmental and health burdens associated with combustion and electric vehicles. *Methodology:* A systematic review was conducted using the Scopus database, with a focus on papers published between 2005 and November 2023. The search was refined to include only English-language publications investigating passenger vehicles, resulting in a final corpus of 75 studies. *Results:* The review revealed that LCA conclusions for automotive vehicles can vary widely depending on the specific study's scope, methodology, and goals. Many studies emphasize the need for a holistic approach considering various drive technologies, production aspects, and local geographical conditions. *Theoretical contribution:* This paper contributes to the field of environmental science and sustainability by synthesizing the current state of knowledge on the environmental impact of vehicles across their entire life cycle. The findings highlight the importance of a nuanced and comprehensive approach to understanding and mitigating the environmental externalities of transportation. *Practical implications:* The insights from this review can inform policymakers, manufacturers, and consumers in their decisions regarding sustainable transportation solutions. By understanding the key areas of concern and improvement opportunities across the entire life cycle of vehicles, stakeholders can work towards a more environmentally responsible and sustainable transportation system.

**Keywords:** Life Cycle Assessment, LCA, vehicle life cycle, electric vehicle, environmental impact

## 1. Introduction

While Battery Electric Vehicles (BEVs) offer clear benefits, declaring them unequivocally "more environmentally friendly" than Internal Combustion Engine Vehicles (ICEVs) is complex. True, BEVs generate no tailpipe emissions, unlike ICEVs, contributing to cleaner air during operation. However, a complete picture of their environmental impact demands looking beyond just the usage phase. To accurately compare BEVs and ICEVs, we must consider the emissions associated with their entire life cycle, from production to disposal.

An utterly objective comparison of the environmental impact between ICEVs and BEVs should also include the ecological costs associated with electricity production, the extraction and processing of fossil fuels, and the manufacturing of vehicle components, including batteries, throughout their entire lifespan, including the decommissioning phase. In other words, it is crucial to adopt an approach that facilitates the analysis of the environmental impact over the entire vehicle life cycle. Achieving a comprehensive understanding of the environmental impact of vehicles necessitates a nuanced approach that accounts for the full spectrum of contributing factors across their entire life cycle. Neglecting this holistic perspective and focusing solely on a single facet risks generating misleading conclusions and impeding informed decision-making regarding sustainable transportation solutions.

Similar to any manufactured product, vehicles generate environmental externalities throughout their life cycle, from the initial extraction of raw materials to their final disposition. A product's Life Cycle Assessment (LCA) can serve as a cornerstone in the design process, encompassing a thorough consideration of its environmental impact throughout its entire life cycle. The LCA method enables an analytical determination of the environmental impact of the product in various stages of its life cycle:

- extraction, processing, and/or delivery of raw materials;
- manufacturing/production;
- introduction into the market - transportation, distribution, and marketing activities;
- use, reuse, and maintenance of the product;
- End-of-life of the product (recycling and disposal).

Life Cycle Assessment offers a comprehensive framework for evaluating a product's or process's environmental impact across its entire life cycle. This holistic approach considers both resource utilization (inputs) and emissions generated (outputs). Typical input data for LCA analyses include natural resources, raw materials, water, energy, and chemicals. Product, by-products, solid waste, harmful dust and gas emissions, water pollution, and soil contamination are all potential input considerations within the LCA framework (Subramanian Senthilkannan Muthu, 2020). By rigorously evaluating these inputs and outputs at each stage of a product's life cycle, LCA facilitates the development of strategies to minimize environmental burdens.

The ISO 14040 standard serves as the cornerstone for conducting Life Cycle Assessments (LCA), providing a structured framework for evaluating the environmental impact of a product or process across its entire life cycle. This comprehensive approach encompasses four key stages:

1. definition of the goal and scope (involving the selection of the product/item, data collection methods, determination of the boundaries of the analyzed system, and choosing the reference unit);
2. analysis of input and output sets (entailing the investigation of the technological process of the product, compilation of flows of raw materials, energy, and auxiliary materials, as well as waste) - (Life Cycle Inventory – LCI);
3. impact assessment (utilizing impact category indicators) - Life Cycle Impact Assessment – LCIA;
4. interpretation of results and conclusions.

When conducting a life cycle assessment (LCA) of a product, it is imperative to ascertain the impact category, establish category indicators, and delineate models characterizing the impact. The ISO 14040 and ISO 14044 standards serve as benchmarks for LCA, offering guidance and directives for environmental assessments of products. These standards categorise environmental impact categories as "ecological categories" or "impact categories." Through LCA, estimating a catalogue of environmental effects associated with a product becomes feasible, influencing the natural environment at local, regional, and global scales. ISO 14040 and ISO 14044 standards define the guidelines for Life Cycle Assessment and provide directives for conducting environmental assessments of products. These

standards classify environmental impact categories as "ecological categories" or "impact categories". Within these categories, it is noteworthy to mention the following:

- climate change (carbon footprint),
- ecological footprint,
- water footprint,
- soil acidification,
- eutrophication,
- toxicity to humans and living organisms,
- energy footprint,
- ozone layer depletion potential,
- photochemical ozone creation potential,
- depletion of biotic and abiotic resources,
- land use.

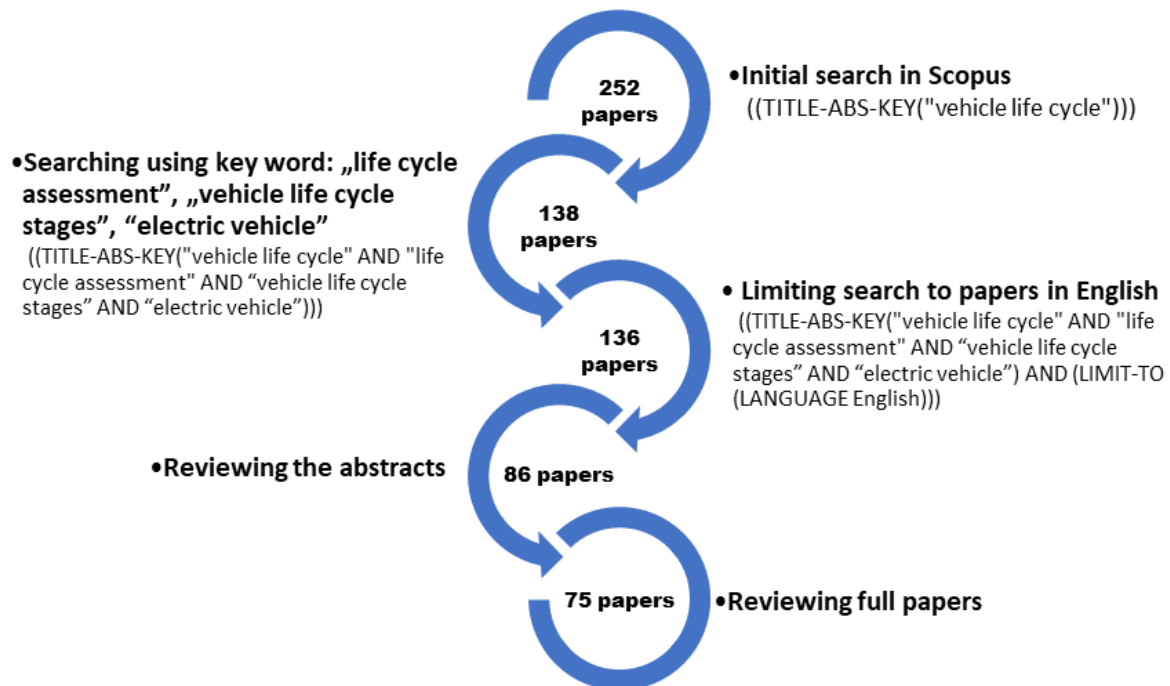
The LCA methodology can be classified based on the levels of detail in its execution (Rybczewska-Blazejowska & Palekhov, 2018):

- cradle-to-grave - a comprehensive life cycle assessment covering all stages of the life cycle;
- cradle-to-gate - an LCA evaluation focusing solely on the processes of resource extraction, production, manufacturing, packaging, and transportation. It assesses only activities that occur within the factory, excluding the phases of distribution, use, and disposal;
- cradle-to-cradle - an extension of the cradle-to-grave method, where the final stage of the product involves the recycling process, ensuring that the product is not discarded after its end of life but is reintroduced into the usage period.

This study aims to advance knowledge in the methodology of environmental life cycle assessment (LCA) for vehicles and to discern potential environmental and health burdens associated with both combustion and electric vehicles. It has been noted that in the earliest life cycle assessments of vehicles with different powertrain types, electric vehicles were consistently regarded as having the least emissions. However, in more recent studies, each stage of the vehicle life cycle is examined in greater detail, taking into account various environmental impact categories. The principal aim of this review is to identify commonly employed methods, models, and indicators in the environmental impact assessment of vehicle life cycles. The analyses and methodological recommendations presented in previously published works that utilized the LCA model to evaluate the environmental efficiency of vehicles are intended to assist researchers in planning new studies within the domain of vehicle life cycle assessments.

## **2. Literature review methodology**

In conducting a comprehensive literature review on the life cycle of vehicles, the author primarily utilized the Scopus database for its expansive coverage of relevant academic journals and proceedings. The initial literature search employed the keyword phrase "vehicle life cycle" within the Scopus database, yielding 252 scientific papers. Subsequent refinements incorporated additional keywords such as "life cycle assessment," "vehicle life cycle stages," and "electric vehicle" to enhance the search precision ((TITLE-ABS-KEY("vehicle life cycle" AND "life cycle assessment" AND "vehicle life cycle stages" AND "electric vehicle") AND (LIMIT-TO (LANGUAGE English)))). Following an initial broad search, the selection was refined to include only English-language publications, resulting in 136 papers. Next, the initial abstract screening refined the selection criteria to encompass studies investigating passenger vehicles exclusively. This resulted in a final corpus of 75 studies that were meticulously examined. Each full paper was rigorously assessed for its relevance to the review's thematic scope and potential to offer substantive contributions.

**Figure 1: Flowchart of the literature review methodology**

Drawing upon 75 papers, this summary synthesizes the extracted information regarding vehicle life cycle assessments:

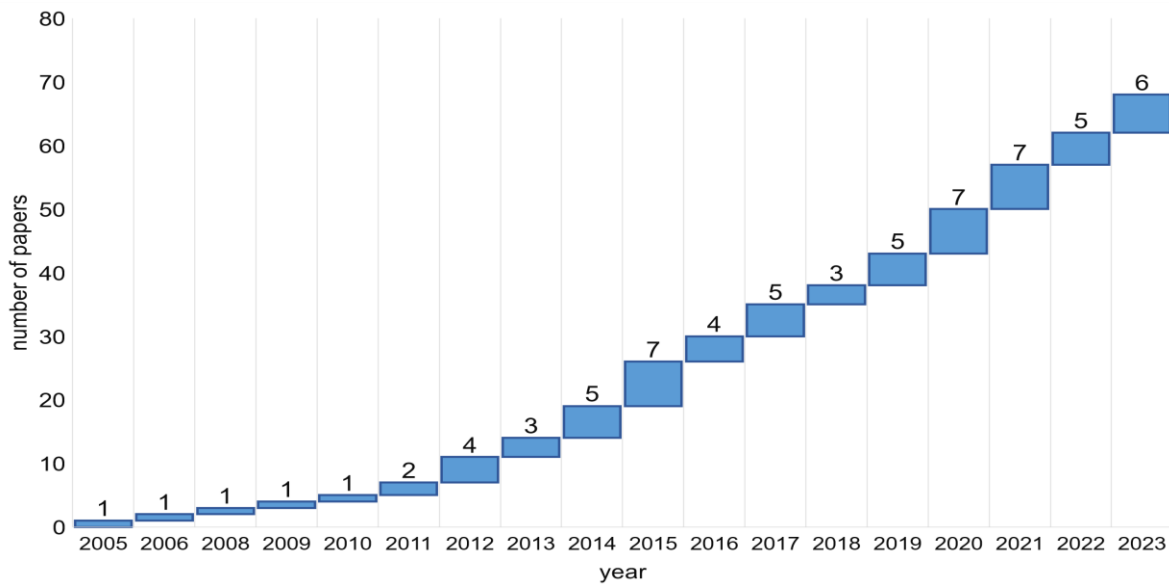
- the years of conducted analyses varied, spanning from 2005 to November 2023;
- subject areas and journal of article publication - journals and thematic areas covered a wide range, including environmental sciences, environmental engineering, transportation engineering, and sustainable development;
- the country (region) for which LCA was conducted – studies using the LCA method to analyze the vehicle life cycle were conducted worldwide, encompassing various countries in different regions of the world;
- the level of detail of the environmental life cycle assessment method for vehicles (e.g., cradle-to-grave, WTW);
- tools used in LCA - various tools can be applied to assess the life cycle, including software for environmental life cycle analysis, modeling and simulation tools, as well as various environmental databases;
- diversity in vehicle types analyzed: The reviewed studies assessed a broad spectrum of vehicle types, including combustion engine vehicles, electric vehicles, and hybrids, often comparing their environmental impacts;
- environmental impact assessment encompassed a breadth of categories, including greenhouse gas emissions, resource consumption, and natural resource degradation, with further focus on specific life cycle stages;
- LCA analysis revealed key aspects, such as critical life cycle stages, vehicle comparisons, and improvement suggestions.

### 3. Results

#### 3.1. Annual publications, subject area and journal

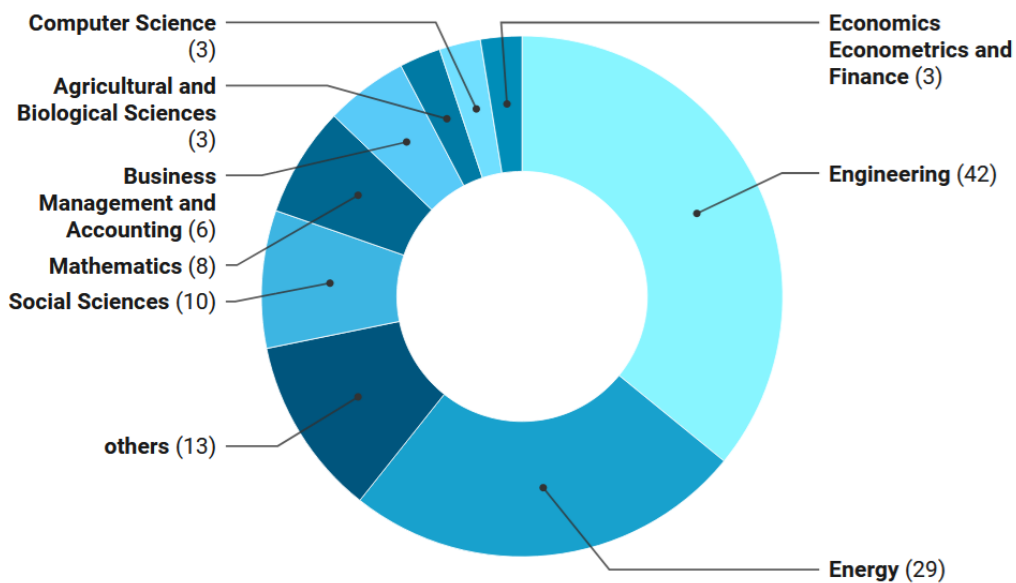
While early studies regarding vehicle life cycles appeared in the Scopus database as early as 1996, this review focuses on papers published between 2005 and November 2023. Figure 2 depicts the yearly distribution of these papers for further analysis.

**Figure 2: Yearly distribution of papers**



By 2010, 10 papers had been published, utilizing Life Cycle Assessment for the evaluation of vehicle lifecycle. The primary emphasis of the subject and analytical methods revolved around conducting an environmental assessment of vehicles featuring various powertrains, considering the "well-to-wheel" (WTW) fuel lifecycle. From 2011 to 2020, 45 studies were published, mainly focusing on detailed analyses of environmental aspects at various stages of the vehicle lifecycle, encompassing different types of powertrains and the production cycle of fuel/energy. From 2021 to the end of November 2023, 18 works were published, with 6 of them in 2023. This confirms that the environmental assessment of the lifecycle remains pertinent, and notably, there is a discernible increase in interest in this subject. The LCA method continues to be an effective tool in this context. Figure 3 displays the subject areas covered by the reviewed papers addressing LCA topics.

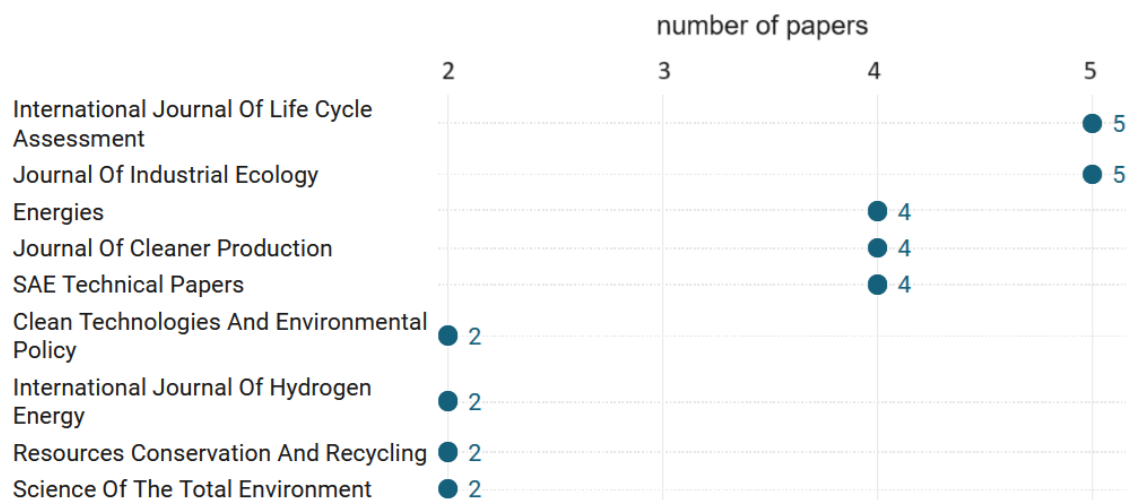
**Figure 3: Subject areas of the reviewed papers**



A predominance of reviewed papers originates from the domains of environmental science, engineering, and energy, indicating that vehicle life cycle assessment research primarily resides within

these disciplines. Fields such as social sciences, mathematics, management, computer science, and economics are also represented to a lesser extent.

**Figure 4: Top 10 journals publishing papers on vehicle LCA**



The predominant focus of articles related to the environmental life cycle assessment of vehicles was observed within the domains of Environmental Science, Engineering, and Energy. Approximately 70% of the identified articles were disseminated within these disciplines. The leading journals in terms of publication frequency were Energy, International Journal of Life Cycle Assessment, and Journal of Industrial Ecology.

### 3.2. Methodology of conducting environmental life cycle assessment of vehicles - a review

#### 3.2.1. Setting the goals and scope of the analysis

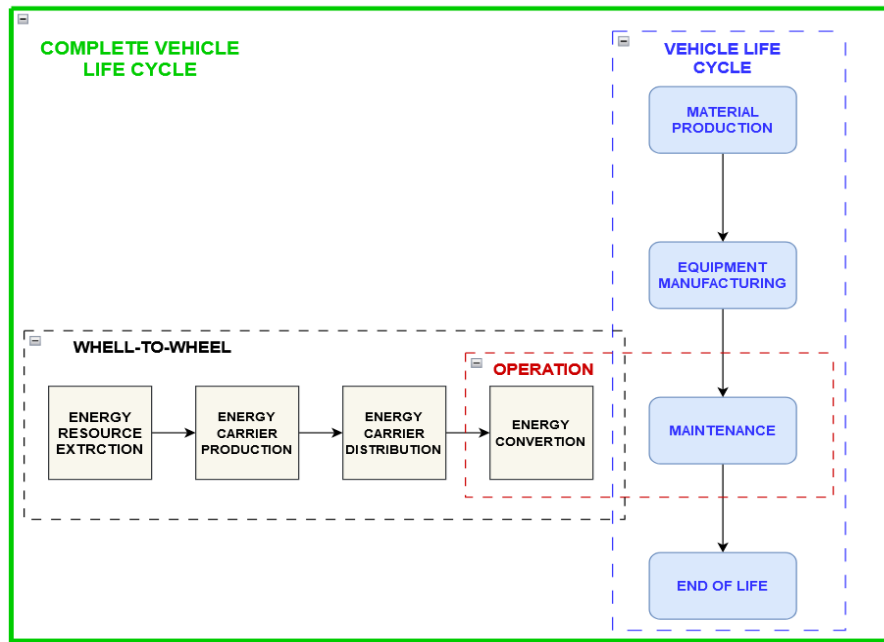
When conducting an LCA analysis for a vehicle, the first step involves defining the scope of the assessment and adopting a reference unit, commonly expressed in kilometers (km) in the majority of analyzed studies. Determining the reference unit allows for the comparison of the environmental impact of vehicles with different types of powertrains. The scope of the life cycle impact assessment of a vehicle can be carried out with varying levels of detail. A comprehensive assessment of the vehicle's life cycle should cover the entire life cycle, known as "cradle-to-grave," as well as the life cycle of the fuel/energy that powers its energy source (WTW – well-to-wheel).

The vehicle life cycle (cradle-to-grave) can be divided into four stages:

- Design stage – involves determining the vehicle's appearance, specifying its equipment, and establishing the materials used in its production. These choices significantly influence the later methods and production technology applied. The envisioned features of the vehicle impact its ecological properties in subsequent stages. This stage is often overlooked in analyses.
- The production and assembly stage encompasses activities such as raw material extraction and processing, manufacturing materials, components, assemblies, and transportation.
- Usage stage – involves the vehicle's operation, technical maintenance, and periods of inactivity.
- End-of-life stage – includes dismantling the vehicle and sorting its components into those suitable for partial reuse, recycling, or disposal as waste.

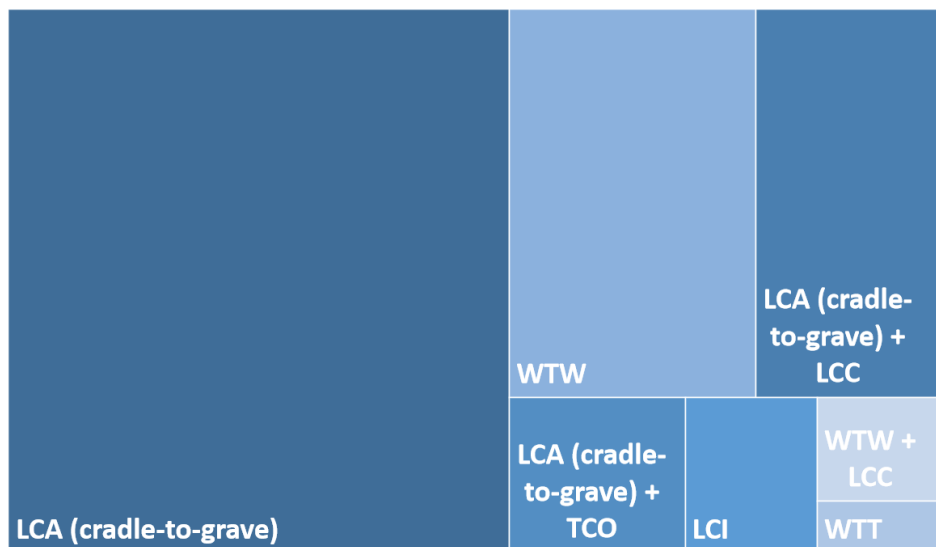


Figure 5: The vehicle lifecycle



The Well-to-Wheel (WTW) analysis is dedicated to examining the life cycle of the fuel or electric energy utilized for the vehicle's energy source. This WTW cycle can be partitioned into two distinct stages: Well-to-Tank (WTT) and Tank-to-Wheel (TTW). The WTT stage centers on processes such as resource extraction, production, distribution, transportation, and storage of the fuel. The TTW phase represents the operational period where the vehicle's fuel/energy is consumed. The environmental impact during the WTT stage is contingent on the methodology employed in fuel or energy production. In the literature on vehicle life cycle assessment, the publications can be categorized based on whether they consider the fuel production stage or exclusively concentrate on the vehicle life cycle—from its manufacturing through usage to its end-of-life (Figure 6).

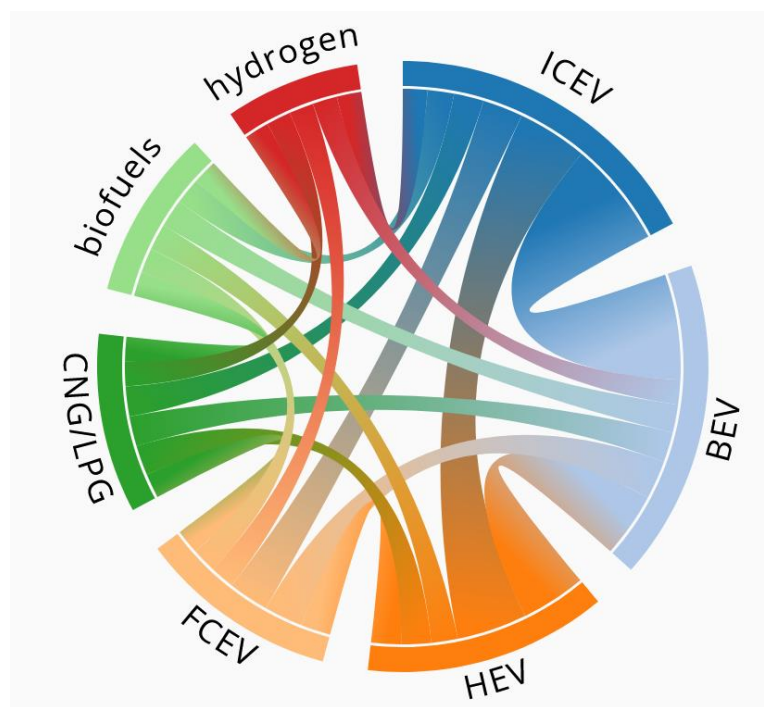
Figure 6: Life cycle assessment methods used in the reviewed papers



A review of LCA studies on vehicle life cycles reveals frequent comparisons of environmental impact of conventional and alternative powertrains. Differences arise from the extraction and processing of materials and resources required for vehicle component manufacturing, energy intensity of production processes, the usage phase, and the potential for material recovery in recycling after the

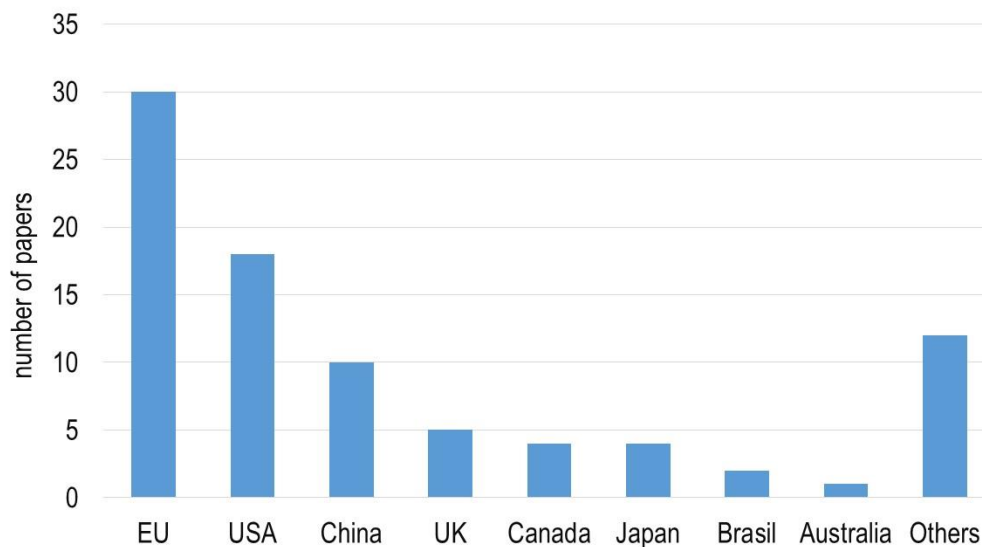
vehicle is retired from service. Beyond the powertrain itself, the chosen fuel/energy source and its production method significantly impact environmental performance. Current research often focuses on individual powertrain types without considering fuel production. These studies are predominantly centered on electric vehicles, exploring the environmental implications of diverse battery technologies (Yang et al, 2018; Van den Bossche et al, 2006), specific energy sources used for electricity generation (Rapa et al, 2020; Kucukvar et al, 2022), battery recycling methods (Koroma et al, 2022). Most analysed publications involve applying the LCA method for the comparative assessment of various powertrain technologies (Figure 7). Most authors opt to compare electric and conventional vehicles. Electric vehicles (BEVs) are the most popular subject, with 18 studies directly comparing their life-cycle impacts to Internal Combustion Engine Vehicles (ICEVs) across various environmental and health impact categories. Another 15 studies use LCA to compare conventional, electric, and hybrid vehicles. The studies investigate the environmental footprint of vehicles with various powertrains (ICEV, BEV, HEV, FCEV) and fuels (diesel, gasoline, CNG, LPG, hydrogen, biofuels).

**Figure 7: Vehicle types in LCA studies**



The geographic scope selection constitutes a critical step in conducting a comprehensive vehicle life cycle assessment, including relevant environmental impacts across various stages. In many studies, authors emphasize that both the usage location and the region substantially impact the results of Life Cycle Assessment (LCA) at all stages of the vehicle life cycle. A vehicle's environmental impact during the production phase can vary significantly depending on the sources of energy used. Compared to countries with renewable-heavy energy mixes, electric vehicles charged using coal-generated electricity contribute more to greenhouse gas emissions and air pollution. The method of energy production also plays a significant role in charging the batteries of electric vehicles and plug-in hybrid vehicles. Fuel production methods are crucial for the environmental impact of all vehicles, not just electric ones. Government policy has a decisive impact on the overall environmental footprint of a vehicle. Implementing sustainable production of vehicles and their components, as well as effective recycling practices, plays a crucial role in minimizing the environmental impact of the automotive industry.



**Figure 8: Distribution of LCA research on electric vehicles based on country of analysis**

Analyzing the number of works analyzing specific countries (Figure 8), it can be noted that the majority of analyses focus on vehicles produced and used in the USA (18 papers). These works encompass emissions analyses and other impacts of vehicles, considering various types of powertrains, with a particular emphasis on the well-to-wheel (WTW) fuel lifecycle. A significant portion of the studies concentrates on the environmental aspects of electric vehicles in the Chinese market (10 papers). The latest research on electric vehicles emphasizes the importance of considering the entire energy chain, from fuel extraction to electricity generation, to assess their environmental impact accurately. Many studies analyzing the life cycle of vehicles with various types of powertrains have been conducted for European Union countries. Out of all retrieved articles, over 40% encompass LCA analyses for EU countries.

The selection of a specific tool for the life cycle analysis of vehicles depends on the specific research context, data availability, analysis scope, and researcher preferences. Many computer programs and tools are used in conducting life cycle analysis of electric vehicles (Table 1).

**Table 1: LCA software tools**

Software	Number of papers
REET	18
Ecoinvent	5
SimaPro	4
IO-LCA model	2
OpenLCA	2
Ecoscore	1
EIOLCA methodology	1
TBL-LCA model	1
GaBi	1
ReCiPe	1
EXIOBASE 3.4	1
Tsinghua-LCA, Model (TLCAM)	1
Author-developed LCA model	37

In the analyzed studies, the most commonly used tool was REET. The REET program (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) is a tool created by Argonne National Laboratory, enabling the life cycle analysis of vehicles with various powertrain types and different types of fuels used in automotive vehicles. Another popular tool is the Ecoinvent, which contains data on many production processes that can be utilized in life cycle analysis. It is often used in conjunction with other tools.

A widespread tool for product life cycle assessment is SimaPro. SimaPro software allows for the assessment of the impact of various aspects of production, usage, and disposal of vehicles with different types of powertrains. In about half of the analyzed studies, authors proposed their own models to determine the environmental aspects of the vehicle life cycle. These models take into account various aspects related to the production, operation, and disposal of vehicles to provide a comprehensive environmental assessment. In most cases, they are developed for a specific vehicle model, type of fuel or powertrain, and local conditions, taking into consideration data availability. Author-specific models of the environmental impact of vehicles are linked to data published in life cycle assessment databases by research institutions, environmental agencies, and other organizations collecting information on the environmental impact of products.

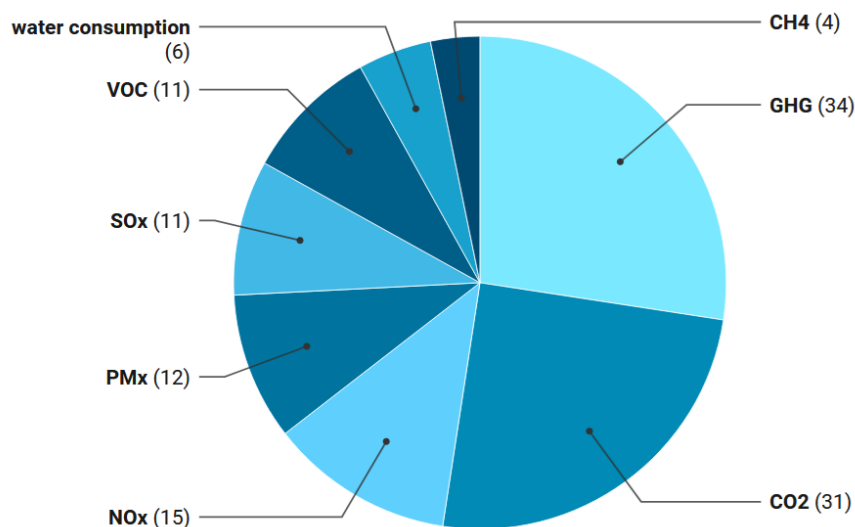
### 3.2.2. Life Cycle Inventory (LCI)

The next stage in LCA, inventory analysis, relies on comprehensive data collection. This involves measuring the exact amounts of materials, energy, and emissions associated with each process in the vehicle's life cycle. Data serves as the basis for developing material and energy balances. In each stage of the life cycle, there are consumed materials, which are input quantities, including, among others, fossil fuels, mineral resources, plastics, construction materials, water, and electrical energy. Each life cycle stage also generates adverse effects of the processes occurring in it, referred to as output quantities. These include, among others, the emission of harmful particulate and gaseous compounds, greenhouse gas emissions, solid and liquid waste, noise emissions, and electromagnetic radiation.

During the production stage, input data includes information on the consumption of natural resources and materials (e.g., steel, aluminium, plastics), energy consumption, fuel consumption, and other chemical substances related to the production of individual vehicle components, such as the body, engine, or battery in the case of electric vehicles. Output data includes greenhouse gas emissions resulting from production processes and the consumption of natural resources (e.g., water consumption, raw material consumption).

During the usage phase, the input data primarily consists of the amount of fuel consumed or electric energy used during operation. Output data include values of greenhouse gas emissions and air pollutants associated with the vehicle's operation. The final stage, End-of-Life, concentrates on maximizing material recovery and environmentally sound disposal methods for retired vehicles. In this phase, input data include materials and chemical substances subject to reuse, recycling, or disposal, along with the accompanying energy consumption, fuel, and other chemical substances associated with the applied recovery methods. Output data includes secondary materials obtained from recycling and emissions related to disposal and recycling processes.

**Figure 9: Most frequently reported output data in LCA analyses of vehicles**



The input and output data accuracy depends heavily on details such as vehicle models, technology, location, manufacturing processes, driving habits, and recycling systems. Therefore, LCA analyses are most effective when tailored to the specific vehicle and local context. In most analyzed studies, the output data summarizing the life cycle impact of the vehicle on the environment included CO<sub>2</sub> emissions, GHG emissions, and other particulate and gaseous substances, with six studies also examining water consumption.

### 3.2.3. Life Cycle Impact Assessment (LCIA)

The next step of the Life Cycle Assessment involves classifying the input and output data into relevant environmental impact categories. The ISO standard distinguishes three main protected areas affected by the vehicle's life cycle. These are human health, the natural environment, and resources (ISO 14000). For each impact domain, the assessment framework utilizes quantifiable indicators to determine the analyzed product's environmental contribution. The methodology employed to calculate these indicator values differentiates between mandatory and optional activities, providing transparency and flexibility in the assessment process. After acquiring quantified indicator values, the vehicle's environmental impact is evaluated through dedicated computational algorithms associated with each impact category. This comprehensive analysis enables the precise identification and quantification of the vehicle's environmental footprint across various domains. Examples of impact categories of the vehicle's life cycle on the natural environment include climate change, depletion of the ozone layer, eutrophication, depletion of mineral and water resources, reduction of fossil fuel reserves, soil acidification, smog formation, ecosystem poisoning, deterioration of human health, and transformation of areas with natural ecosystems.

**Table 2: Categories of environmental impact of the vehicle life cycle in the reviewed papers**

Impact categories of the vehicle's life cycle	Number of papers
Climate change	22
Human toxicity	17
Global Warming Potential	15
Particulate matter formation	13
Acidification	12
Photochemical oxidant formation	10
Depletion of abiotic resources – minerals and metals	9
Water use	6
Land use	6
Freshwater eutrophication	5
Ozone depletion	4
Terrestrial acidification	4
Depletion of abiotic resources – fossil fuels	4
Terrestrial ecotoxicity	3
Freshwater depletion	3
Ionizing radiation	2
Natural land transformation	2
Eutrophication	2
Freshwater ecotoxicity	2

The disparity in the number of articles published across each category signifies the varying degree of research interest directed towards diverse environmental facets associated with the life cycle of vehicles employing different propulsion technologies. Comparative studies on the environmental impact of different propulsion technologies can be conducted by analysing the impact of different types of vehicles in different categories. Most studies address the impact of vehicles on climate change. This category focuses on greenhouse gas emissions, such as CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O, and their impact on climate change.

In numerous studies, the impact of vehicles on human health has been analyzed. The category of human toxicity provides information on chemical substances that may be toxic to humans at various life cycle stages, from production through usage to disposal.

Global Warming Potential holds particular importance among the essential environmental impact categories considered in vehicle life cycle assessment. It assesses the influence of greenhouse gas emissions on the atmospheric ability to retain heat, ultimately contributing to global warming. The unit commonly used in this category is the carbon dioxide equivalent indicator (CO<sub>2</sub>e). The study also examines the impact of the vehicle life cycle on particulate matter formation. This category involves the analysis of solid particle emissions associated with various phases of the vehicle's life and their impact on air quality and human health.

Numerous studies have emerged investigating the impact of vehicle life cycles on emissions that contribute to soil, water, and atmospheric acidification, with detrimental effects on ecosystems. Additionally, the assessment of vehicle life cycles frequently incorporates a broader range of impact categories, including photochemical oxidant formation, depletion of abiotic resources – minerals and metals, water use, and land use.

### **3.2.4. Life Cycle Assessment results interpretation and conclusions**

The ultimate phase of the life cycle assessment analysis comprises the nuanced interpretation of the obtained results, a succinct synopsis of the analytical processes, and the formulation of conclusive statements. This final stage delivers a well-structured list of the environmental impact categories exerted by the analyzed object. Additionally, recommendations aimed at mitigating negative environmental impacts are provided. The profound significance of the LCA lies in its ability to bridge the gap between analysis and real-world application, yielding practical knowledge that empowers stakeholders to improve the vehicle's design, production, or usage in a manner that fosters sustainable development. Conclusions drawn from conducting an environmental life cycle assessment for a motor vehicle can vary, depending on the purpose and granularity of the analysis.

The conducted LCA allows for the recognition of the impact category that predominates throughout the entire vehicle life cycle. Identifying specific life stages of the vehicle (production, usage, disposal) enables a focus on areas requiring the utmost attention, thereby proposing specific solutions to reduce the overall environmental impact throughout the life cycle. In many studies, LCA results indicate that the production stage of electric and hybrid vehicles represents a significant environmental burden (Del Pero et al., 2018). An assessment of the impact on mineral resource depletion reveals that, within the spectrum of technologies employed in electric vehicles, those dependent on critical raw materials for the propulsion system exhibit the highest level of impact within this category (Messagie et al., 2014; Asaithambi et al., 2019; Mayyas et al., 2017).

For example, a study (Qiao et al., 2017) showed that the CO<sub>2</sub> emissions in the production phase of an electric vehicle are about 60% higher compared to internal combustion engine vehicles (ICEV). The high environmental impact is mainly due to the production of lithium-ion batteries. A key factor contributing to this impact is the process of mining, processing, and distributing the metals used to produce the electrodes (Notter et al., 2010). The cumulative emissions generated during electric vehicle manufacturing are considerably higher than those generated by conventional vehicles (Messagie et al., 2010). The results of the LCA analysis presented in the study (Onat et al., 2014) indicate that the production phase exhibits the most significant socio-economic impact compared to other life cycle stages of the analyzed vehicle. In contrast, the use phase dominates in terms of environmental impact and certain socio-economic effects, such as human health and the economic costs of emissions. Many studies have indicated that replacing ICEVs with electric vehicles can shift the environmental impact from the vehicle use phase to the production phase (Li et al., 2018; Patterson et al., 2012).

As indicated in the papers (Koroma et al., 2022; Cox et al., 2020; Mitropoulos et al., 2017), a long lifespan of an electric vehicle can significantly reduce its environmental impact throughout its life cycle. The study (Danilecki et al., 2023) reported that a lifespan that is too short, no longer than the average car use limit in the EU, will not offset the environmental burdens of the production phase. In the work (Li et al., 2019) further showed that an electric vehicle's lifetime CO<sub>2</sub> emissions correlate with its weight.

By applying LCA methodologies, numerous studies have investigated the environmental performance of vehicles by utilizing diverse powertrain technologies. The outcomes of these analyses, dependent upon the chosen assumptions, assessed impact categories, and year of analysis, elucidate the presence of significant disparities between powertrain technologies. The main conclusion from LCA studies is that transport electrification significantly reduces the consumption of fossil fuels, but

greenhouse gas emissions are strongly dependent on the sources of electricity generation (Elgowainy et al., 2009; Ou et al., 2010; Ivanov et al., 2020; Tang et al., 2021). The location of electric vehicle use also matters, as the method of electricity production in a given region affects the level of emissions from electric and plug-in hybrid vehicles during the use phase (Moro & Lonza, 2018; Bouter et al., 2020; Petrauskienė et al., 2021; Franzò & Nasca, 2021; Fusco Rovai et al., 2023; Małek et al., 2023). Numerous studies present the results of LCA analyses of electric vehicles in various energy scenarios, as presented in the works (Jursova et al., 2019; Rapa et al., 2020). A study described in the paper (Nandola et al., 2023) estimated that in order for electric vehicles to be characterized by the lowest CO<sub>2</sub> emissions in the Well-to-Wheel (WTW) cycle, at least 44% of electricity must come from non-fossil fuel sources. The authors of the work (Messagie et al., 2014) emphasized that a scenario where electricity generation is restricted to fossil fuels like crude oil or coal might induce a level of climate change impact potentially equivalent to the emissions generated by conventional vehicles.

Considering emissions at the point of use, many studies have emphasized that electric vehicles (EVs, HEVs, PHEVs) seem to be a better option for urban driving (Karabasoglu & Michalek, 2017; Van Mierlo et al., 2017; Szumska, 2021; Zheng & Peng, 2021; Šarkan et al., 2023). The results presented in the paper (Noshadravan et al., 2015) point out that during the use stage, factors such as charging location, average distance traveled in urban mode, average daily mileage and driving aggressiveness can have a significant impact on the environmental footprint of both electric and conventional vehicles.

Drawing upon their life-cycle assessments (LCA) findings, the authors present a series of recommendations to enhance the end-of-life recycling and disposal processes for vehicles. These proposed solutions are intended to facilitate a reduction in waste generation and a concomitant limitation in the consumption of natural resources. A study (Liu et al., 2022) employed LCA to reveal that greenhouse gas emissions during the recycling of electric vehicles with batteries substantially impact their life cycle more than vehicles with internal combustion engines. Moreover, numerous studies suggest that developing advanced recycling techniques capable of maximizing material recovery across the entire life cycle could significantly reduce greenhouse gas emissions (Safarian, 2022).

Based on the findings of LCA studies, numerous recommendations have been put forward for vehicle manufacturers regarding the materials used in production, technological processes, and waste management strategies, all to minimize the environmental impact of vehicles. Many researchers suggest that reducing emissions in the life cycle of hybrid vehicles can be achieved by using an internal combustion engine powered by alternative fuels, such as natural gas (Heidary et al., 2023; Nandola et al., 2023), biofuels (Andersson & Börjesson, 2021; Moreira et al., 2022), or hydrogen (Wong et al., 2021). As exemplified in the research presented in (Timmermans et al., 2006; Paulino et al., 2018) the implementation of novel technologies within internal combustion engines, explicitly targeting the reduction of air pollutant emissions, demonstrably facilitates a decrease in emissions during vehicle operation and additionally contributes to a reduction in the overall WTW emissions. The findings of the analyses presented in the paper (Samsu Koroma et al., 2023) demonstrate that integrating electric powertrain components into a compact unit can potentially reduce the consumption of rare metals and minerals, thereby enhancing resource utilization efficiency and mitigating the environmental impact throughout the material supply chain. In the work (Soo et al., 2015) adoption of lightweight materials and multi-material design principles in automotive manufacturing has been strategically directed towards creating more environmentally sustainable vehicles. This approach has demonstrably resulted in a significant reduction in carbon dioxide emissions during the vehicle use phase, consequently facilitating compliance with increasingly stringent emission regulations. The papers (Aboushaqrah et al., 2021; Buberger et al., 2022; El Hafdaoui et al., 2024) emphasized that fuel and energy production should be carried out in a sustainable and environmentally friendly manner, which unfortunately can be economically challenging.

Based on LCA results, many studies identify the roles and influence of various stakeholders, such as consumers, suppliers, and regulators, in shaping more sustainable practices associated with each stage of the vehicle life cycle. The benefits of LCA activities for society, the economy, and the environment are also highlighted. This information can form the basis for strategies supporting sustainable development. The paper (Koroma et al., 2023) demonstrates that developing practical strategies for improving waste management in mines and companies processing metals and raw materials could reduce the toxicity indicators associated with producing electric vehicles. In addition, improving recycling rates and processes for automotive materials can minimize the negative impact of



metal mining activities. Based on the results of the LCA, the paper (Bauer et al., 2015) stated that the electrification of road transport should be accompanied by the integration of life cycle management in vehicle production chains and energy and transport policy to counteract potential environmental burdens. Drawing upon the findings of the LCA analyses presented in (Mohammadi Ashnani, 2015), the authors posit that efficacious policies governing vehicles and fuels do not necessitate the imposition of specific solutions such as electric vehicles or biofuels. Instead, they advocate for establishing performance and emissions-based fee standards, which would ostensibly empower the market to identify and implement the most optimal and impactful alternative.

#### **4. Discussion and conclusions**

This work undertook a systematic analysis of scientific literature employing the life cycle assessment methodology within the context of passenger vehicles. Drawing upon a dataset of 252 papers from Scopus, this study conducted a systematic review of 75 selected works to examine the application of the life cycle assessment (LCA) methodology to vehicles with diverse drive systems. The review meticulously considered each analysis's research stages, objectives and scope, the specific object of study, the employed methods and tools for environmental performance assessment, the evaluated impact categories, and the resulting conclusions.

Based on the conducted review, it can be stated that the results of LCA analysis of passenger vehicles can be diverse depending on the scope, methodology, and objectives of a particular study. Many papers emphasize the complexity of the life cycle analysis of vehicles and the need for a holistic approach to assessing their environmental impact, encompassing various drive technologies, production aspects, and local geographic conditions. Moreover, it was noted that many publications focus on the life cycle analysis of vehicles, omitting the fuel or energy production stage. However, to fully understand the environmental impact, it is necessary to consider both of these aspects. A literature review reveals that numerous studies have compared the environmental impact of different drive train technologies, with a particular focus on conventional vehicles versus electric vehicles. It has been noted that LCA requires consideration of the geographic area, as both the location of use and the region can influence the results of the analysis. The impact of energy production and government policy are of significant importance for the final environmental assessment of a vehicle.

An essential step in conducting a vehicle LCA is the analysis of a quantitative dataset pertaining to each stage of the vehicle's life cycle: production, use, and end of life. The specific input and output data adopted in the research vary depending on the assumptions made, the specific vehicle, the drive technology, the production location, the mode of use, and the recycling system. The majority of analyses summarize the environmental impact of a vehicle's life cycle primarily through the evaluation of CO<sub>2</sub>, greenhouse gas (GHG), and other particulate and gaseous emissions. Notably, some studies additionally incorporate water consumption as an ancillary parameter for impact assessment.

The conclusions derived from this comprehensive review underscore the critical need for comprehensive initiatives and actions aimed at minimizing the environmental footprint of vehicles throughout their life cycle, including design, production, and utilization. Furthermore, the recommendations emanating from the LCA studies possess the potential to serve as invaluable guidance for the automotive industry's pursuit of sustainable development initiatives.

It is essential to acknowledge that certain limitations exist despite this review's extensive and thorough nature. Firstly, the review exclusively considers articles published between 2005 and 2023 that are included in the Scopus database. Works from other major scientific databases, such as Web of Science/Clarivate or Google Scholar, were not considered. However, it is worth noting that a significant portion of the analyzed works are indexed in multiple databases. Secondly, the present review of papers encompasses 75 works, whereas the number of studies could be significantly higher if the search was expanded to include other databases. Thirdly, no detailed values of environmental performance indicators for vehicles in specific impact categories were presented. Although such information was provided in the reviewed papers, only the main conclusions of the review were presented.

This work comprehensively synthesises existing life cycle assessments conducted on passenger vehicles. Drawing upon insights and methodological recommendations gleaned from previous research, it offers valuable support to researchers by enabling more detailed analyses of the various stages within a vehicle's life cycle. In light of the trend towards increasingly precise research, this article strives to



provide a holistic perspective on the ecological implications associated with vehicles. This approach aims to transcend the limitations of one-sided conclusions solely derived from the use phase, thus ensuring a broader and more specific understanding.

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## Ethics approval and consent to participate

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## Availability of data and material

The data are available on request.

## Competing interests

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