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Review

A Narrative Review of Life Cycle Assessments of Electric Vehicles: Methodological Challenges and Global Implications

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Abstract

Considering the rapid global shift towards electric mobility and the growing importance of life-cycle assessments (LCAs) in policy and investment decisions, a critical examination of the methodological challenges and broader implications of electric vehicle (EV) life-cycle assessments is both timely and necessary. While numerous studies have assessed the environmental impacts of EVs using LCA, there remains a lack of consolidated insight into how methodological inconsistencies, particularly in system boundaries, functional units, and data sources, affect the comparability and policy relevance of results. This article addresses this gap by presenting a narrative review of LCA applied to EVs, with a focus on methodological approaches and environmental impact categories. The review aims to synthesize current knowledge, identify prevailing research trends, and highlight key methodological challenges in the LCA of EVs. A structured search was conducted using the Scopus database, initially yielding 1926 publications through a broad search strategy. To improve relevance and reduce the number of marginally related articles, the search was refined to include only article titles, resulting in 187 studies selected for detailed analysis. The VOSviewer software was employed to perform bibliometric and co-occurrence analysis, revealing key clusters in the literature related to battery production, electricity mix, and recycling.

Keywords: battery electric vehicles (BEV); electric vehicles (EV); environmental impact; life cycle assessment (LCA); Scopus search strategy; sustainability; narrative review

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1. Introduction

Transportation accounts for nearly a quarter of greenhouse gas emissions in Europe and is a major contributor to urban air pollution [1]. In 2022, the Environmental Protection Agency (EPA) reported that transportation accounted for 29% of total U.S. greenhouse gas emissions (both direct and indirect), ranking third after accounting for indirect emissions from distributed electricity [2]. Growing concerns about climate change, urban air pollution, and energy security have accelerated the search for sustainable mobility solutions. Among the available alternatives, electric vehicles (EVs) have garnered significant attention as a means to decarbonize road transport. Their potential to minimize CO_2 emissions and reduce reliance on fossil fuels makes them a key technology for achieving global carbon neutrality goals.

Electromobility has become a central element in the transformation of modern transportation, combining decarbonization goals with rapid technological innovation. The importance of electric vehicles has grown year by year, reflected not only in public debate but also in increasing academic interest. To substantiate this claim, we present an analysis of the number of scientific publications on electric vehicles between 2000 and 2024, which shows a clear upward trend (Figure 1). This increase in knowledge production suggests that this topic is gaining strategic importance for public policy, industry, and future empirical research, as indicated by the Scopus database.

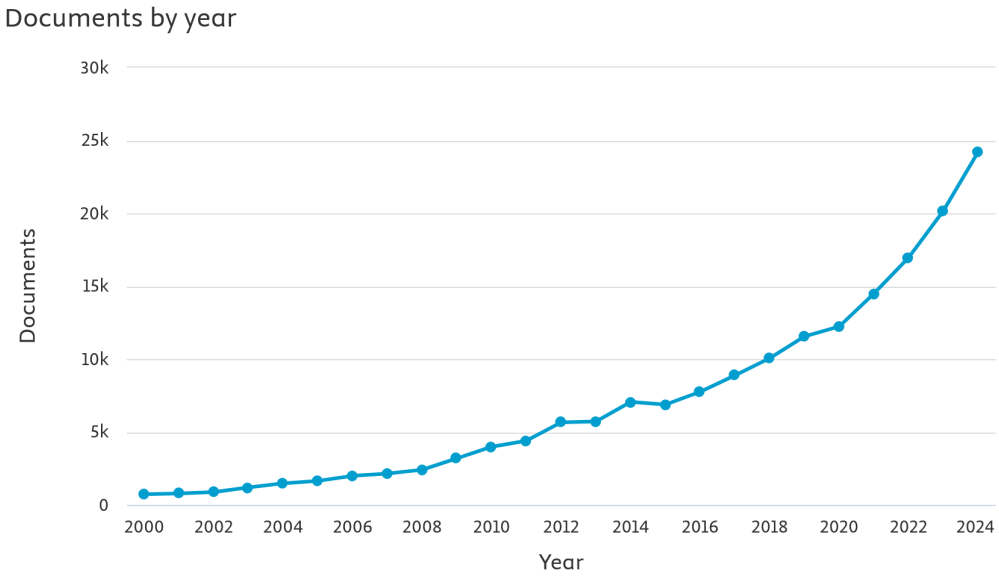


Figure 1. Publication Trends on Electric Vehicles in Scopus, 2000–2024 [3].

The number of scientific publications on electric vehicles (EVs) has increased dramatically over the past two decades. In 2000, only 732 publications were recorded, whereas by 2024 the number reached 24,215, representing an over 30-fold increase. The increasing number of publications on electric vehicles not only reflects their technological and environmental importance but also underscores the growing need to assess their full environmental impact. While EVs are often promoted as a cleaner alternative to conventional vehicles, their overall sustainability depends on factors such as battery production, electricity sources, and end-of-life management [4–6].

Life Cycle Assessment (LCA) provides a comprehensive framework to evaluate these impacts across all stages, from raw material extraction to manufacturing, use, and disposal. According to ISO 14040 and ISO 14044 family (ISO 14040:2006 [7]; ISO 14044:2006 [8]; ISO/TS 14048:2002 [9]; ISO/TR 14049:2012 [10]; ISO/TS 14067:2018 [11]; ISO 14071:2014 [12], and ISO 14072:2014 [13], LCA can be defined as the process of collecting and analyzing data on the resources used, emissions generated, and potential environmental effects of a product system across all stages of its life cycle [14].

Despite the rapid expansion of research on electric vehicles (EVs) within the context of Life Cycle Assessment (LCA), and a substantial number of review publications on this topic [15–20], the existing body of literature still exhibits notable fragmentation. Most reviews focus on specific subsystems or technologies, such as lithium-ion battery chemistries [21–24], fuel-cell vehicles [25], or hybrid configurations [26], while others address isolated life cycle stages, such as battery production [27] or end-of-life treatment n [28]. Consequently, relatively few works provide a comprehensive and methodologically consistent synthesis that encompasses the entire vehicle system. However, none of the existing reviews has provided a comprehensive synthesis of the differences in system boundary

definitions and allocation methods applied in LCA studies of electric vehicles (EVs). These aspects represent critical methodological challenges, as inconsistencies in their treatment often lead to contradictory or non-comparable results at the global scale.

At the methodological level, inconsistencies remain a critical challenge. Variations in system boundaries, functional units, allocation methods, and assumptions about the electricity mix contribute to substantial differences in LCA outcomes. Studies such as Marmiroli et al. [29] and Nordelöf et al. [30] have shown that these methodological discrepancies can explain a significant share of the variability in reported results, thereby limiting the comparability and policy relevance of existing findings. Yet, few reviews investigate the underlying causes of such divergences or propose harmonized frameworks to address them.

Another important limitation lies in the narrow geographical scope of most assessments. Existing reviews typically rely on data and scenarios from specific regions, such as Europe, North America, or East Asia, without adequately accounting for global heterogeneity in electricity mixes, vehicle technologies, and end-of-life management systems. This lack of a global, integrative perspective hinders the understanding of how regional differences collectively influence the overall environmental performance of EVs.

Taken together, these limitations reveal a clear research gap, i.e., although numerous studies assess EVs using the LCA framework, there is still no globally oriented synthesis that consolidates methodological insights, quantifies sources of variability, and evaluates implications for sustainable transport policy. Building upon this, previous research on Life Cycle Assessment (LCA) of electric vehicles (EVs) has addressed a wide range of issues, yet many studies remain largely descriptive in nature or focus primarily on policy-oriented discussion. However, only a limited number of publications have critically and comprehensively examined methodological inconsistencies, particularly how differences in system boundary definition, functional units, or data transparency hinder cross-study comparability and weaken the scientific foundations for evidence-based policymaking.

Therefore, the main objective of this article is to fill this gap by conducting a narrative review of life cycle assessments of electric vehicles, focusing on methodological challenges, key influencing factors, and global implications. The study aims to provide a comprehensive synthesis of the literature, identify prevailing methodological inconsistencies, and offer guidance for the future harmonization of LCA approaches in the EV sector.

Accordingly, this review provides a unique and innovative contribution to the existing literature. For the first time, we analyze and compare the methodological challenges in LCA studies of electric vehicles (EVs). We also demonstrate how these methodological differences directly shape and distort global implications, for instance, contrasting LCA outcomes for countries dominated by coal-based versus renewable electricity mixes. By moving beyond a mere compilation of results, this review offers a critical analysis and synthesis of the existing evidence, thereby providing a conceptual framework for methodological standardization in future LCA studies of electric vehicles.

2. Materials and Methods

The research methodology consisted of two main stages. The first stage involved defining appropriate keywords to achieve the highest possible precision in identifying articles related to the topic under investigation, namely, electric vehicles and life cycle assessment (LCA). The second stage involved using VOSviewer (version 1.6.20) to perform a graphical analysis of the results obtained in the first stage, with a specific focus on the co-occurrence of keywords relevant to the subject matter.

The literature review was conducted using the Scopus database to identify relevant peer-reviewed articles focusing on life cycle assessments (LCA) of electric vehicles. This

search was in accordance with the PRISMA guidelines, and the screening and selection process is illustrated in Figure 2.

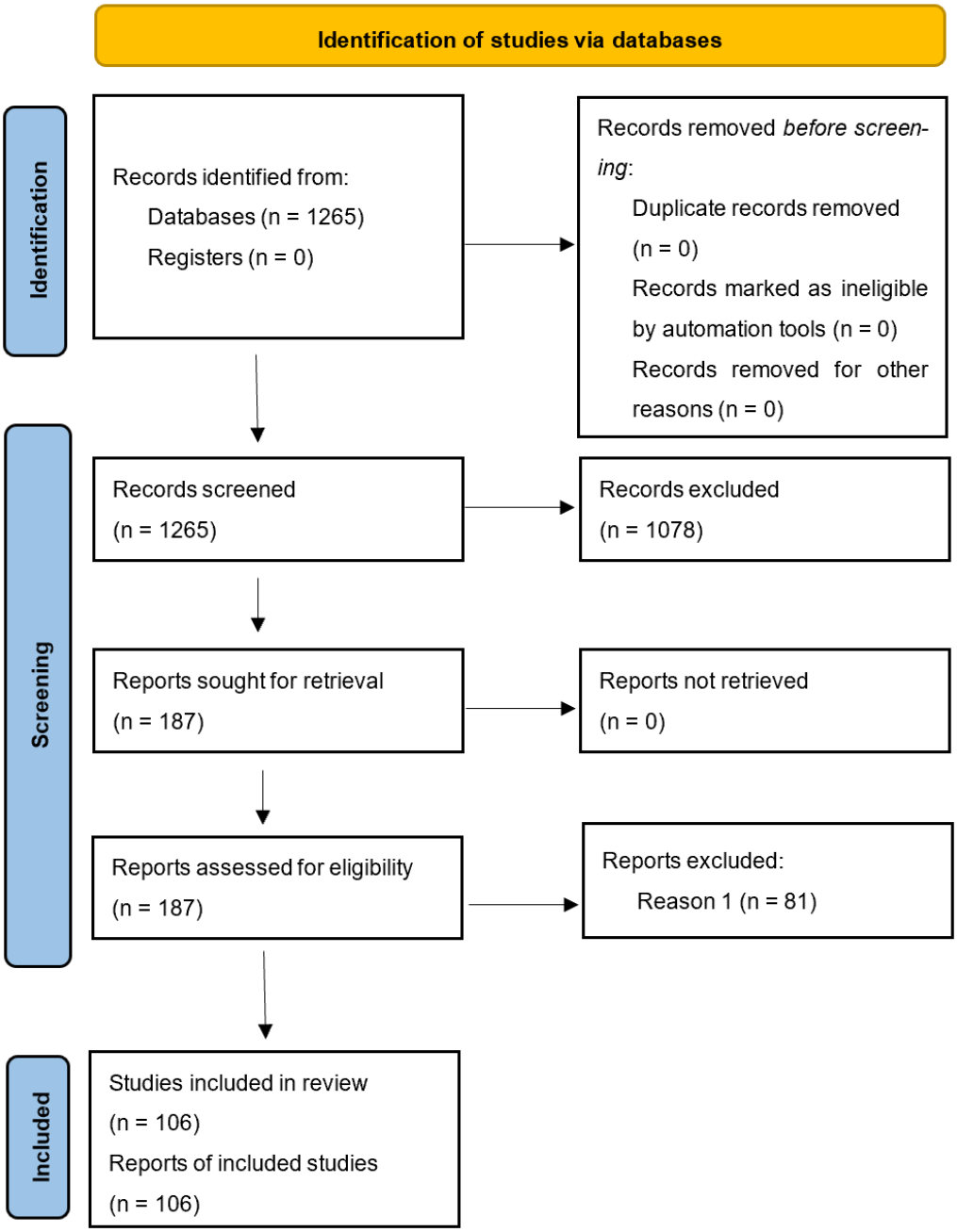


Figure 2. PRISMA Flow Diagram according to PRISMA 2020.

The initial search string included multiple variations of key terms such as "electric vehicle*", "EV", "battery electric vehicle*", "BEV", and "life cycle assessment", applied across the TITLE-ABS-KEY fields. The string was as follows: TITLE-ABS-KEY ("electric vehicle*" OR "EV" OR "battery electric vehicle*" OR "BEV" AND "life cycle assessment" OR "LCA"). The initial search using the full scope returned 1265 results. The vast majority of which, despite the presence of keywords in the abstracts, were not directly related to the subject of the study. This meant a need for manual selection of a very large number of publications that were not substantively relevant, which in practice reduced the efficiency of the review process and increased the risk of subjectivity in assessing topical relevance. Therefore, we decided to narrow the search to titles only, which yielded 187 results much

better aligned with the topic. To ensure the greatest possible completeness of the review, each of these publications was thoroughly analyzed. This step was intended to improve topical relevance and reduce the inclusion of marginal or unrelated studies. The TITLE-only search produced 187 articles, a more manageable and focused dataset in which core concepts (electric vehicles and life cycle assessments) were central to the research. While this approach may have omitted studies discussing relevant content solely in abstracts or keywords, the trade-off was considered acceptable given the goal of thematic precision and the need to ensure the feasibility of full-text screening. This decision is documented as a methodological trade-off between comprehensiveness and practical constraints, such as time and resource availability. The search strategy and inclusion criteria were applied consistently throughout the screening process.

The research methodology is illustrated in Figure 3.

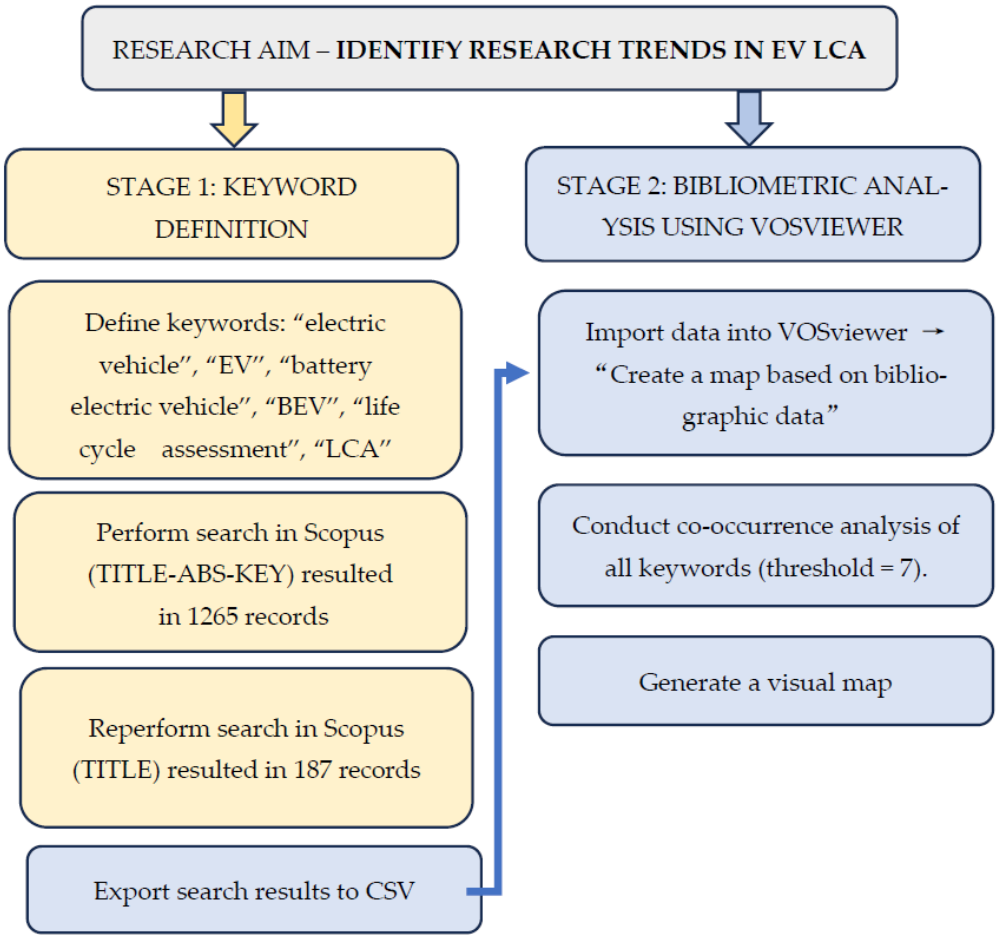


Figure 3. Research methodology procedure.

The next step involved generating a map in VOSviewer to visualize the co-occurrence of keywords and identify the main research themes and their relationships within the literature on electric vehicle life cycle assessments. All 187 selected articles were exported from Scopus as a CSV file and imported into VOSviewer for bibliometric analysis. In VOSviewer, the option "Create a map based on bibliographic data" was selected, followed by choosing "Read data with bibliographic database files" and specifying the Scopus CSV file containing the search results. Next, the type of analysis was set to co-occurrence, and the unit of analysis was defined as all keywords. A threshold for the minimum number of occurrences of a keyword was set at 7, resulting in 96 out of 1577 keywords meeting this criterion. Finally, a network visualization map was generated, illustrating the relationships

and clustering of keywords across the dataset. This process enabled the identification of major research themes and trends within the literature on life cycle assessments of electric vehicles.

3. Results

3.1. VOSviewer Analysis

The results begin with a bibliometric analysis performed in VOSviewer on the Scopus dataset retrieved for EV LCA. The software generated network maps that visualize the structure of the field through clustered groups of terms that frequently co-occur. These visualizations highlight the dominant thematic areas, reveal interconnections between topics "electric vehicles" and "LCA" and indicate the relative prominence of clusters via node size and link strength. The resulting thematic map provides a basis for identifying the main research domains and guiding the subsequent, more detailed interpretation of trends and gaps. The generated map is presented in Figure 4.

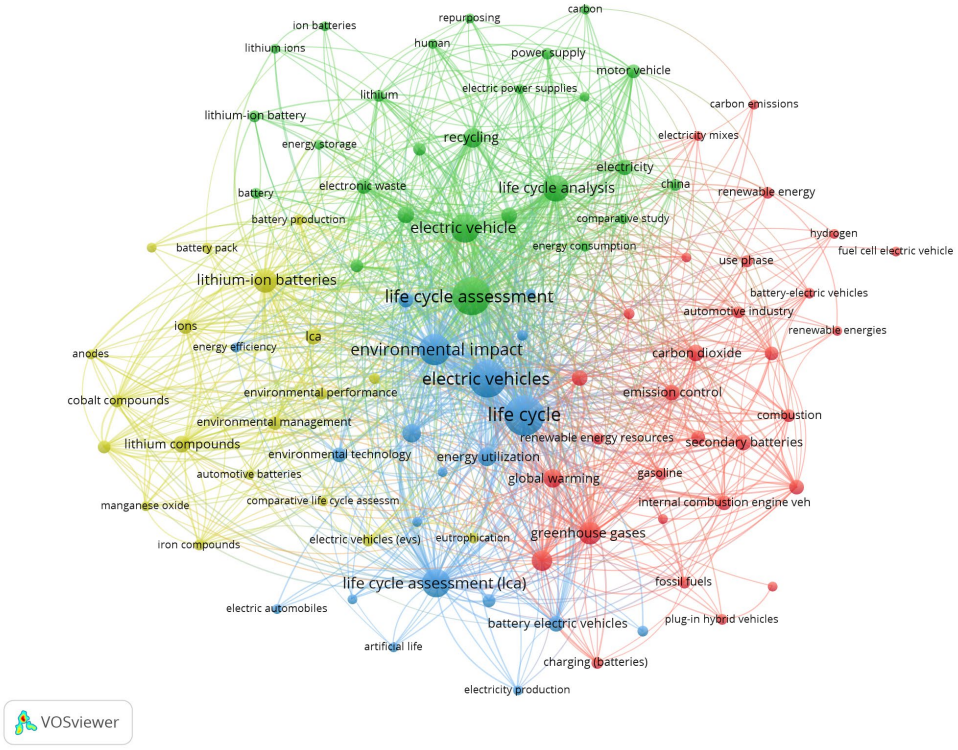


Figure 4. Co-occurrence of keywords generated in VOSviewer.

Figure 4 illustrates a keyword co-occurrence network generated using VOSviewer, based on bibliographic data related to the application of life cycle assessment (LCA) in the field of electric vehicles (EVs), battery technologies, and environmental impacts. Terms are grouped into four clusters using the VOS clustering algorithm, where node size represents keyword frequency and link strength indicates co-occurrence relationships.

Keywords such as "life cycle assessment", "electric vehicles" and "environmental impact" appear centrally in the network, suggesting their foundational role across multiple research streams. Their high link strength implies that they serve as connecting concepts among diverse thematic areas. Blue cluster is connected with Life Cycle Assessment Methodologies and EV Technologies. This cluster focuses on the methodological foundations of life cycle assessment and its application to electric vehicles. Keywords such as "life cycle assessment (LCA)", "electric vehicles (EVs)", "environmental impact", "battery electric vehicles", and "energy utilization" reflect comprehensive environmental impact

analyses of EV systems. The green cluster is characterized by system-level terms such as "electric vehicle", "life cycle assessment", "life cycle analysis", and "recycling." This group demonstrates a strong research focus on comprehensive impact assessment, encompassing the production, usage, and end-of-life phases of EVs. The proximity between the green and blue clusters indicates a strong methodological link between LCA techniques and system-level EV assessments. This suggests that research in these two areas often overlaps, with shared concerns such as system boundaries and environmental trade-offs. The yellow cluster represents a more technical research theme concerning battery chemistries and their environmental profiles. Keywords such as "lithium-ion batteries", "lithium compounds", "cobalt compounds", "iron compounds", "battery production", "anodes", and "manganese oxide" indicate a strong focus on battery component analysis, toxicity assessment, and sustainability of raw materials. The relative isolation of the yellow cluster from others may indicate that studies focusing on battery chemistry tend to be more specialized and less integrated with broader environmental assessments. This fragmentation points to a potential gap in holistic LCA approaches that bridge material-level analysis with system-wide impacts. Red cluster is centered around "greenhouse gases", "gas emissions", "carbon dioxide", "global warming", and "emission control". It captures research focused on the environmental burdens of conventional transportation technologies and comparative analyses with low-emission alternatives.

Based on the VOSviewer keyword co-occurrence map, several thematic areas were identified, corresponding to distinct research clusters. The analysis revealed four main clusters that represent the key directions of research within the field of electric vehicle life cycle studies. The thematic areas identified on the VOSviewer keyword co-occurrence map correspond closely to the analytical structure adopted in this paper. The red cluster, encompassing topics such as carbon emissions, renewable energy, decarbonization, and policy aspects, aligns with Section 3.2. Regional and Country-Specific LCA of Electric Vehicles, which addresses the geographical differentiation of LCA results depending on regional energy mixes and policy frameworks. The blue cluster, which focuses on life cycle assessment (LCA) and environmental impact, directly relates to the discussion presented in Section 3.3. Literature analysis on LCA comparison of electric vehicles with hybrid and conventional combustion engine vehicles. The green cluster, associated with battery technology, recycling, and environmental assessment of lithium-ion batteries, supports the analysis developed in Section 3.4. Strategies for Reducing Environmental Impacts of EVs. Together, these clusters not only visualize the main research domains in the field but also provide a conceptual basis for organizing the discussion and literature review presented in this study. These clusters collectively outline the main thematic domains that structure the current body of research and provide the basis for further analysis in this study.

3.2. Regional and Country-Specific LCA of Electric Vehicles

The environmental impacts of electric vehicles (EVs) can vary significantly depending on regional factors [31], including the electricity generation mix [32], local manufacturing practices [33], and energy policies [34]. Life Cycle Assessment (LCA) studies that focus on specific countries or regions help to capture these variations, providing more accurate and context-sensitive evaluations of greenhouse gas emissions, energy consumption, and other environmental indicators. Understanding these regional differences is crucial for designing effective strategies to maximize the environmental benefits of EV deployment worldwide.

Many studies focus on comparing electric and internal combustion vehicles in terms of environmental impacts [35,36], particularly with regard to exhaust emissions. Most of them converge on the finding that EVs emit fewer greenhouse gases over their life cycle compared to ICEVs, but only under favorable electricity mix conditions. Olindo et al. [37]

reveal significant variability (up to 30%) in the greenhouse gas (GHG) emissions associated with the national production mixes found in leading databases. The research performed by Nimesh et al. [38] indicate that the environmental impact of EV adoption varies by country and is strongly influenced by the proportion of renewable energy in their electricity mix. Specifically, EVs are deemed sustainably feasible in France and Brazil, somewhat feasible in countries like China and India, but not viable in Indonesia.

For example, Burchart-Korol et al. [39] conducted a cradle-to-grave LCA of EVs in Poland and the Czech Republic, comparing them with ICEVs. EVs show lower GHG emissions and fossil fuel depletion but higher impacts on acidification, eutrophication, human toxicity, and particulate matter. The study highlights that renewable electricity use is key to maximizing EV environmental benefits. Messagie M. et al. [40] evaluate the environmental impacts of a battery electric vehicle (BEV) in Belgium. An initial comparison of energy consumption across vehicle technologies highlights that BEVs are less energy-intensive. The study then examines the full life cycle of a BEV, emphasizing the significant impact of manufacturing and the benefits of battery recycling. Overall, BEVs outperform petrol vehicles, except in scenarios where electricity is generated exclusively from coal or oil.

Bartolozzi et al. [41] used LCA to compare hydrogen production scenarios in Tuscany with EVs and Italy's national energy mix. Renewable energy generally reduces impacts, with wind energy being slightly more beneficial. BEVs exhibit lower overall impacts than hydrogen vehicles, whose emissions are higher due to the energy-intensive production, storage, and distribution processes. Life cycle impacts vary by energy source: biomass hydrogen impacts dominate during use, wind hydrogen during production and logistics, while EV impacts are mainly from manufacturing and maintenance. Furthermore, Rovelli et al. [42] applied Consequential Life Cycle Assessment (CLCA) to evaluate the impacts of future BEV adoption in Italy. Without additional renewable capacity, BEV-related climate impacts could rise by ~40%.

Results by Hawkins et al. [43] show that EVs, using the current European electricity mix, offer a 10% to 24% reduction in global warming potential (GWP) compared to conventional diesel or gasoline vehicles over a 150,000 km lifespan. However, EVs have higher impacts on human toxicity, freshwater eco-toxicity, freshwater eutrophication, and metal depletion, mainly due to the vehicle supply chain. Since production impacts are more significant for EVs, assuming a 200,000 km lifespan increases GWP benefits to 17–29% compared to gasoline and 17–20% compared to diesel vehicles. A 100,000 km assumption reduces the benefit to 9–14% for gasoline vehicles, making the impacts comparable to those of diesel vehicles.

Joshi et al. [44] assess the life cycle GHG emissions of ICEVs, BEVs, and FCEVs in Nepal using a cradle-to-grave approach. The study finds that BEVs and FCEVs emit 187 and 922 g CO_2-eq/km, respectively, compared to 507 g CO_2-eq/km for ICEVs over 200,000 km. With increased local electricity availability, upstream emissions could decrease by 88%, resulting in a 50% reduction in total emissions for BEVs and an 82% reduction for FCEVs. Similar studies were performed by Unocc Godoy et al. [45]. They compared the carbon footprint of an electric vehicle (EV) and a gasoline vehicle (ICEV) across their entire life cycle, from manufacturing to recycling. The analysis accounted for South Korea's electricity mix in the production phase and Peru's energy mix during operation under varying mileage scenarios. Results show that at lower mileages, the emission differences between EVs and ICEVs are small. However, at higher mileages, gasoline vehicles produce substantially more CO_2.

In turn Shang et al. [46] developed an LCA model in China to compare air pollutant and GHG emissions of EVs and ICEVs. Their results show that EVs cut life cycle emissions by 12% CO_2, 69% NOx, and 9% VOCs, with production, particularly the manufacturing

of lithium batteries, identified as the main challenge. By 2025, widespread EV adoption could reduce 3.55 million tons of CO_2, 36,289 tons of NOx, and 4315 tons of VOCs, with most reductions occurring during the driving phase. Results [47] show that electric vehicles with vehicle–road coordination cut life cycle carbon emissions by 20–22%, compared to 16–20% for fuel vehicles. On highways, reductions are 12–15% for electric vehicles versus 3–6% for fuel vehicles. Electric vehicles are projected to have approximately 30% lower life-cycle carbon emissions and a 29% lower environmental impact compared to fuel vehicles. Scenario analysis shows that, under China's current electricity mix, electric vehicles emit 24–31% more carbon than comparable fuel vehicles [48].

Ahmadzadeh et al. [49] find that BEV emissions are highly dependent on the U.S. electricity mix, with charging methods, battery density, and lightweighting strategies having a strong influence on overall impacts. Higher-density batteries and aluminum reduce weight and increase driving range but raise production emissions, partially offsetting life cycle benefits. Huo et al. [50] assessed the fuel-cycle greenhouse gas (GHG) and air pollutant (NOx, SO_2, PM_{10}, $PM_{2.5}$) emissions of electric vehicles (EVs) in China and the U.S., focusing on six major, highly populated regions in each country. Results indicate that EV emissions are strongly dependent on the carbon intensity and cleanliness of the electricity mix, with significant regional variations. In areas with low coal usage, such as California, EVs substantially reduce GHG and most air pollutant emissions compared to conventional vehicles. In regions dominated by coal, such as parts of China and the U.S. Midwest, EVs lower GHG emissions but may increase total and urban air pollutants. Under scenarios where EVs are charged with 80% renewable electricity or the cleanest coal-fired technologies, reductions of 60–85% in GHGs and air pollutants are possible. Kawamoto et al. [51] proved that regional variations in power generation are decisive. In low-carbon regions, BEVs outperform ICEVs, but in coal-dependent regions, the advantage may vanish. Zheng et al. [52] quantify this threshold, estimating that BEVs only surpass ICEVs if average power generation emissions fall below ~320 g CO_2/kWh.

Faria et al. [4] conduct environmental and economic LCAs of conventional (gasoline and diesel ICEVs) and electric vehicles (PHEVs and BEVs), focusing on primary energy sources and operational GHG emissions. Results show that a high renewable share does not always ensure low EV emissions due to source variability. Driving style and climate control use can raise energy consumption by up to 47% and 60%, respectively. Overall, EVs can outperform conventional vehicles in terms of sustainability, provided that battery technology advances, eco-driving practices are adopted, and low-carbon electricity is utilized. Xia et al. [53] emphasized that EV production, especially battery manufacturing, results in higher environmental burdens than ICEVs. However, during use, EVs perform better, especially when powered by cleaner energy sources. Other results [54] indicate that BEVs produce 10% to 86% fewer greenhouse gas (GHG) emissions than conventional gasoline vehicles.

Shafique et al. [55] compare cradle-to-grave life cycle impacts of EVs across ten countries under current and future electricity mixes. Results show that Chinese EVs have a higher impact, while Norway's 2030 mix yields the lowest. Overall, cleaner future electricity significantly reduces the environmental harm associated with EVs, emphasizing the need for the adoption of renewable energy.

Overall, cleaner future electricity significantly reduces the environmental harm associated with EVs, emphasizing the need for the adoption of renewable energy. To place these results in context, the next section examines how electric vehicles perform relative to conventional combustion engine vehicles.

3.3. Literature Analysis on LCA Comparison of Electric Vehicles with Hybrid and Conventional Combustion Engine Vehicles

Beyond regional and energy-mix variations, several studies have examined how technological characteristics, operational conditions, and future energy scenarios influence the life-cycle environmental performance of electric and conventional combustion engine vehicles. A substantial body of research has compared the environmental performance of electric vehicles (EVs) and internal combustion engine vehicles (ICEVs) using Life Cycle Assessment (LCA) approaches [35,36]. These studies collectively reveal that while EVs substantially reduce tailpipe emissions and fossil fuel use, their overall environmental superiority depends on electricity generation mix, battery production processes, and vehicle lifetime assumptions. A consistent conclusion across studies is that EVs shift the environmental burden from the use phase to the production phase, particularly battery manufacturing, which can offset some of the operational gains if electricity is carbon-intensive.

Findings presented by Song et al. [56] indicate that the total potential environmental impact of an electric vehicle over its entire life cycle amounts 0.17 kg CO_2 per kilometer when averaged across 150,000 km.

Feng et al. [57] examine lithium nickel cobalt manganese oxide (NCM) and lithium iron phosphate (LFP) batteries that are currently the most commonly used types in China's electric vehicle market. The findings indicate that LFP batteries generally offer better environmental performance than NCM batteries, although their energy efficiency during the usage phase is lower. NCM batteries, on the other hand, offer higher recycling value. Among recycling methods, hydrometallurgical processes deliver superior results. Overall, battery recycling can reduce environmental and resource-related impacts by 5–30%, making it a crucial strategy for promoting sustainable development.

Marques et al. [58] presented a comparative LCA from cradle to grave of two battery chemistries: LFP and lithium manganese oxide (LMO), taking into account real-world usage conditions and battery capacity degradation over time. The results show that LFP batteries outperform LMO batteries in terms of operational efficiency, requiring fewer replacements over the vehicle's lifetime. However, LFP batteries have higher life cycle environmental impacts, primarily due to more energy-intensive manufacturing processes.

Several studies focus on emerging battery technologies, including innovative anode and cathode materials and experimental chemistries such as lithium–sulfur, magnesium–sulfur, or silicon nanostructure-based batteries. These technologies have the potential to increase energy density and improve performance, although they are not yet widely used in electric vehicles. Benveniste et al. [59] conducted research comparing LCA using a "cradle-to-grave" system boundary for Li-ion batteries, specifically Nickel–Cobalt–Manganese (NCM) and Li-Sulfur batteries, in electric vehicles. The results highlight the environmental advantages of Li-S technology, particularly in terms of natural resource depletion, where Li-S batteries show 70–90% lower impact values compared to conventional lithium-ion (NCM) batteries.

Degen et al. [60] evaluated the environmental impacts of lithium-ion, sodium-ion, and solid-state battery (LIB, SIB, and SSB) cells. Through a cradle-to-gate LCA, it was found that producing LIB cells currently results in approximately 58–92 kg CO_2-eq per kWh of cell capacity and requires 296–624 kWh of cumulative energy demand (CED) per kWh. SIB cell manufacturing emits around 75–87 kg CO_2-eq/kWh, while SSB cells range from about 88–130 kg CO_2-eq/kWh, depending on the electrode design. Design and manufacturing process optimizations could reduce the environmental footprint of cell production by up to 38% in the near term, potentially lowering the GWP to approximately 37 kg CO_2-eq/kWh for LFP cells and 44 kg CO_2-eq/kWh for NMC900 cells.

Study performed by Wang et al. [61] assessed the life cycle impacts of lithium-ion batteries using silicon nanowire (SiNW) and silicon nanotube (SiNT) anodes, both of which raise concerns due to toxic chemical use and potential nanoparticle emissions during production. Using LCA and a cradle-to-gate approach, two 63.5 kWh battery packs were compared. Both models have NMC cathodes, but differ in anodes (SiNW vs. SiNT). Results show that the NMC-SiNW battery requires more materials and causes greater environmental impacts than the NMC-SiNT battery to deliver the same capacity.

Many of the presented scientific studies focus on electric vehicles (EVs) in the context of greenhouse gas (GHG) emissions, as understanding their life cycle environmental impacts is crucial for developing sustainable transportation solutions and guiding policy decisions toward low-carbon mobility. Numerous studies have analyzed the life cycle greenhouse gas (GHG) and CO_2 emissions of electric vehicles (EVs) and their batteries. Table 1 summarizes key life cycle greenhouse gas (GHG) and CO_2 emissions data for different electric vehicle types and battery chemistries, highlighting variations across production and use stages.

Table 1. Life Cycle GHG and CO_2 Emissions for EVs and Battery Technologies.

Vehicle/Battery Type	GHG/CO_2 Emissions	Life Cycle Stage	Reference
Li-ion (LIB)	91.21 kg CO_2-eq per kWh	Production	Chen et al. [62]
	154.1 kg CO_2-eq per kWh	Use	
Lithium-ion LIB	105 kg CO_2-eq per kWh	Production	Wu et al. [63]
Lithium-ion (LIB)	58–92 kg CO_2-eq per kWh	Production	Degen et al. [60]
Sodium-ion (SIB)	75–87 kg CO_2-eq per kWh	Production	
Solid-state (SSB)	88–130 kg CO_2-eq per kWh	Production	
LTO EV battery	1860 kg CO_2-eq/kWh	Full life cycle	Yin et al. [64]
Prototype composite battery	1323.9 kg CO_2 per battery	Production	De Sio et al. [65]
Li–O_2 EV battery	149 g CO_2-eq/km	Full life cycle	Wang et al. [27]
FCEV (green hydrogen)	105 g CO_2/km	Use phase	Shet K. et al. [66]
Various batteries	10–394 kg CO_2-eq/kWh	Production	Ankathi et al. [67]
Hydrogen systems	0.40–1.58 kg CO_2-eq/kWh-el	Production and use	Konrad et al. [68]
Li-S (next-gen EV)	158 g CO_2-eq/km	Life cycle (use and production)	Deng et al. [69]

Source: Own elaboration based on literature source.

Table 1 highlights significant variability in emissions depending on battery type, vehicle technology, and life cycle stage. For example, production-phase emissions can be particularly high for conventional lithium-ion batteries and prototype composite batteries, while the use phase dominates for hydrogen and lithium-titanate batteries. The following results on GHG emissions are presented below.

To assess the energy, environmental, and resource impacts of lithium titanate (LTO) batteries used in electric vehicles, Yin et al. [64] performed a life cycle assessment (LCA) model, including second-use stages. The LTO battery is a type of lithium-ion battery that utilizes lithium titanate ($Li_4Ti_5O_{12}$) as the anode material, rather than the more common graphite. Per kWh of capacity, the battery's life cycle impacts were: 28,000 MJ (CED), 1860 kg CO_2eq (GWP), and 4.77 $\times$ 10^{-3} kg Sb eq (ADP(e)). Battery efficiency losses during use were the primary contributors to GWP, while production emissions primarily stemmed from materials such as electrodes, aluminum, and solvents.

The study of De Sio et al. [65] presents a preliminary life cycle assessment (LCA) of a prototype battery pack made from pultruded composite materials (50% glass fiber and 50% nylon). It evaluates CO_2 emissions and cumulative energy demand (CED) across

the battery's life cycle, encompassing production, use, and recycling. Findings show that raw material extraction and the usage phase are the most environmentally impactful, with a CED of 13,629.9 MJ and 1323.9 kg of CO_2 emitted during production for a single EV battery pack. Recycling methods also influence environmental outcomes. Switching from mechanical recycling to pyrolysis increases CO_2 emissions by 4–19%.

Wang et al. [27] also made an analysis of the cradle-to-grave LCA of the lithium oxygen battery for electric vehicles. As a result, the environmental impacts are significantly lower. Specifically, the life cycle greenhouse gas emissions for the Li–O_2 battery are 149 g CO_2-eq per kilometer, which is 9.5% less than those of the NMC-G battery. These findings suggest that Li–O_2 batteries have strong potential as a more environmentally sustainable alternative for future electric vehicle applications.

The research performed by N. Shet K. et al. [66] compares life cycle GHG emissions of FCEVs (Fuel cell electric vehicle) and BEVs (Battery electric vehicle). Green hydrogen-powered FCEVs exhibit the lowest emissions, at 105 g CO_2/km. Blue hydrogen FCEVs emit 141 gCO_2/km, lower than BEVs using the current (185 gCO_2/km) and projected 2030 (141 gCO_2/km) grids. FCEVs offer a sustainable option with blue hydrogen in the near term and green hydrogen in the long term. BEVs have higher fuel cycle emission contributions than FCEVs.

K. Ankathi et al. [67] evaluate the environmental implications of traditional lithium-ion batteries (LIBs) compared with emerging alternatives such as solid-state batteries (SSBs) and sodium-ion batteries (SIBs). Reported greenhouse gas (GHG) emissions from manufacturing range from 10 to 394 kg CO_2-eq per kWh. Lithium manganese cobalt oxide and lithium nickel cobalt aluminum oxide fall toward the higher end of this range (20–394 kg CO_2-eq/kWh). In contrast, lithium-iron-phosphate (34–246 kg CO_2-eq/kWh) and sodium-ion designs (40–70 kg CO_2-eq/kWh) demonstrate lower environmental impacts.

Konrad et al. [68] examine factors such as system design, charging efficiency, hydrogen supply routes, and recharging demand, with a focus on global warming potential (GWP) and energy consumption. Environmental impacts range from 0.40 to 1.58 kg CO_2eq/kWh-el for GWP and 4.95 to 7.68 kWh/kWh-el for energy demand. The hydrogen storage system, primarily due to the use of CFRP, contributes the most to GWP and energy demand during both production and end-of-life. MHP system efficiency impacts the use phase, with hydrogen production being the largest source of energy demand.

Deng et al. [69] presented a detailed and novel LCA model aimed at evaluating the environmental impacts of lithium-sulfur (Li-S) batteries for next-generation electric vehicle (EV) applications. The life cycle impact assessment indicates that battery use contributes approximately 70% of the global warming potential (GWP) and fossil depletion potential (FDP), while battery production accounts for around 28%. The findings show that the Li-S battery offers significant environmental advantages, with 9% to 90% lower impacts across most categories. In terms of carbon footprint, the Li-S battery generates 158 g CO_2-eq per kilometer over its life cycle, compared to 174 g CO_2-eq per kilometer for the NCM-Graphite battery. Another study by Deng et al. [70] conducts a life cycle assessment (LCA) of a next-generation lithium-ion battery using a molybdenum disulfide (MoS_2) anode and an NMC cathode, designed for a 49.4 kWh capacity and 320 km EV range. The MoS_2 synthesis and battery performance are based on lab-scale data. Compared to a standard NMC-Graphite battery, the NMC-MoS_2 version exhibits 6–7% higher global warming and fossil depletion impacts, as well as 141–271% higher toxicity and eutrophication impacts.

Similarly, Fan et al. [71] presented LCA with a 'cradle-to-grave' scope, analyzing lithium iron phosphate (LFP) batteries, lithium nickel cobalt manganese oxide (NCM) batteries, and lead-acid batteries. Lithium-ion batteries have a greater environmental impact during the production stage compared to lead-acid batteries. However, due to their superior

charging and discharging efficiency, they perform better in the usage phase. Overall, LFP batteries demonstrate stronger environmental performance, particularly in terms of carbon emissions, soil acidification, and depletion of non-renewable resources, while lead-acid batteries show advantages in ozone depletion, ecotoxicity, and eutrophication.

Pinto-Bautista et al. [72] present an initial forward-looking assessment of the environmental performance of a conceptual magnesium–sulfur (Mg–S) battery intended for potential application in electric vehicles (EVs). Analysis of the use phase indicates that magnesium-based EVs could achieve environmental performance comparable to lithium-ion battery EVs, while surpassing internal combustion engine vehicles (ICEVs) in several categories.

An interesting study was presented by Lavigne Philippot et al. [73], who evaluated a prototype silicon-rich anode battery compared with graphite-based alternatives. Results showed a lifetime emission of 265 g CO_2-eq/kWh, with cathode paste production as the primary driver of toxicity and resource impacts. The study indicated that silicon-rich anodes may provide benefits only if battery lifetimes exceed 180,000 km; otherwise, their environmental burden outweighs performance gains. Yang et al. [74] further explored silicon nanostructures, confirming that Silicon Nanowires (SiNW) designs require more materials and generate higher environmental impacts than Silicon Nanotubes (SiNT) designs. Together with Wang et al. [61] these studies suggest that silicon-based innovations need careful evaluation to balance performance with environmental consequences. These findings highlight the need for targeted strategies to minimize the environmental trade-offs associated with advanced battery technologies, which are further discussed in the following section.

3.4. Strategies for Reducing Environmental Impacts of EVs

Researchers also devote considerable attention to identifying strategies to minimize the environmental impacts of electric vehicles. These strategies are implemented through multiple approaches, including the development of advanced battery chemistries [75] and design [76] with lower greenhouse gas emissions, optimization of manufacturing processes [77], architecture [78], use of renewable energy in vehicle production [79] as well as charging [35,54,80–83], recycling [84] and second-life applications of batteries [85,86], and improvements in vehicle energy efficiency, highlighting the importance of eco-design [87]. Overall, improving battery and vehicle disposal technologies is crucial for enhancing sustainability [88]. Figure 5 shows the most promising methods for reducing the environmental impact of electric vehicles.

The most significant findings from studies on reducing environmental impact strategies are presented below. Baumann et al. [82] demonstrate the potential of combining hourly resolved LCA with smart charging to reduce the environmental impacts of electric vehicles (EVs). The analysis reveals that the environmental impact of charging varies significantly depending on the electricity mix and the timing of charging. Results indicate that BEV life cycle emissions can nearly double when charged at times with the highest greenhouse gas intensity.

The manufacturing approach [89] designed for high-areal-loading Li-ion battery electrodes offers a key advantage by eliminating the use of the hazardous and expensive NMP solvent. The assessment compared its performance with that of the conventional NMP-based method for a 42 kWh NMC622–graphite battery pack. Results show that dry processing reduces energy use by 4.8% and delivers up to 47.5% lower environmental impacts in 12 of 13 impact categories, underscoring its superiority over traditional NMP-based production.

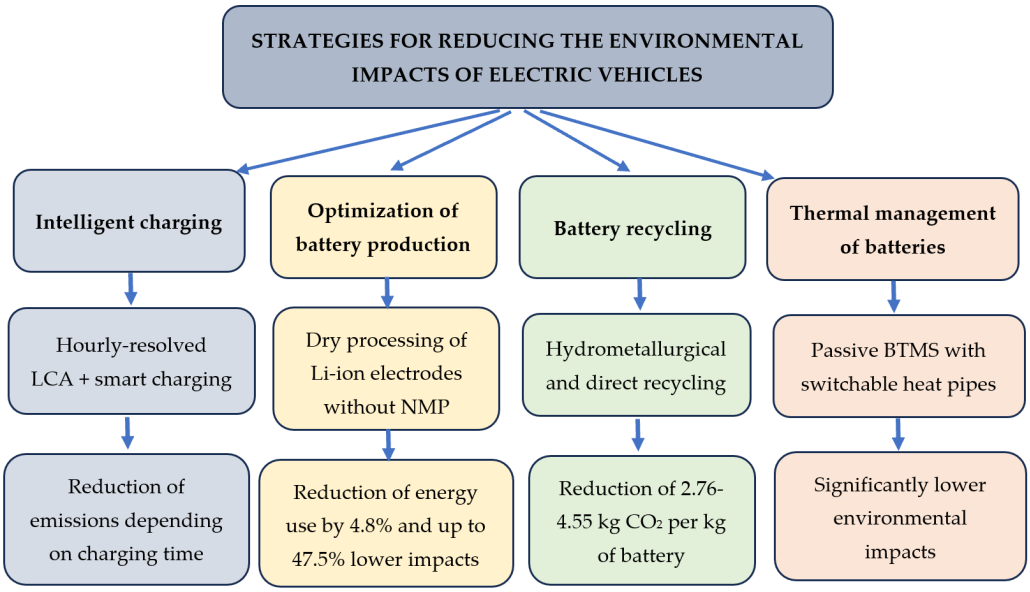


Figure 5. Methods for reducing the environmental impact of EVs. Source: Own elaboration based on: [82,89–91].

The operational stage makes a notable contribution to the overall carbon footprint and other midpoint impact categories [92]. The research by Sung-Hoon Kim et al. [21] demonstrates that battery performance metrics, such as charge–discharge cycles, energy capacity, and energy efficiency, have a greater impact on CO_2 emissions than electricity and energy use during production. For ranges of 300 km or more, battery weight contributes more to the carbon footprint than charge/discharge losses [93].

Rosenberg et al. [90] performed a life cycle assessment (LCA) of two battery recycling methods: hydrometallurgical and direct recycling. Both approaches demonstrated environmental advantages over production from virgin materials, reducing greenhouse gas emissions by 2.76–4.55 kg CO_2e per kg of battery for NMC111 and NMC811 chemistries. This analysis reveals that in such closed-loop systems, the choice of allocation method (cut-off versus avoided burden) can result in substantial differences in ecological benefits, ranging from 0% to 85%. Furthermore, combining both recycling routes in production yields the lowest greenhouse gas emissions for this closed-loop scenario.

Raugei et al. [94] present the first life cycle assessment (LCA) of LCP batteries, incorporating a newly designed hydrometallurgical recycling process that enables recovery of both valuable metals and the graphite component at end-of-life, thereby preventing the CO_2 emissions associated with conventional disposal.

Maike Illner et al. [91] present a novel passive BTMS (Battery Thermal Management System) developed by Fraunhofer CPM, using switchable heat pipes that activate only at a set temperature to transfer heat to a fin-based cold plate. A Life Cycle Assessment comparing this design to an active BTMS shows that the passive system achieves significantly lower environmental impacts across most categories, making it a promising and eco-friendly cooling solution for compact-class EVs.

Held et al. [95] analyzed BEVs in commercial fleet applications. Their results showed that predictable usage and high vehicle utilization enable right-sized battery design, reducing production-related impacts. Monticelli et al. [96] extended this work by comparing battery thermal management systems (BTMS). They showed that loop heat pipe systems substantially reduce weight, resource use, and overall environmental impact compared to conventional cooling plates. These innovations demonstrate how system-level design can improve the sustainability of EV batteries. While various strategies can effectively reduce

the environmental impacts of electric vehicles, their true benefits can only be accurately assessed through consistent and transparent consideration of methodological challenges within LCA studies, as discussed in the following section.

3.5. Methodological Challenges of EVs LCA

Life Cycle Assessment (LCA) is a powerful tool for evaluating the environmental impacts of electric vehicles (EVs). However, the literature reveals significant methodological inconsistencies that undermine the comparability, reproducibility, and policy relevance of findings. Based on the reviewed studies, several key methodological challenges have been identified, as illustrated in Figure 6.

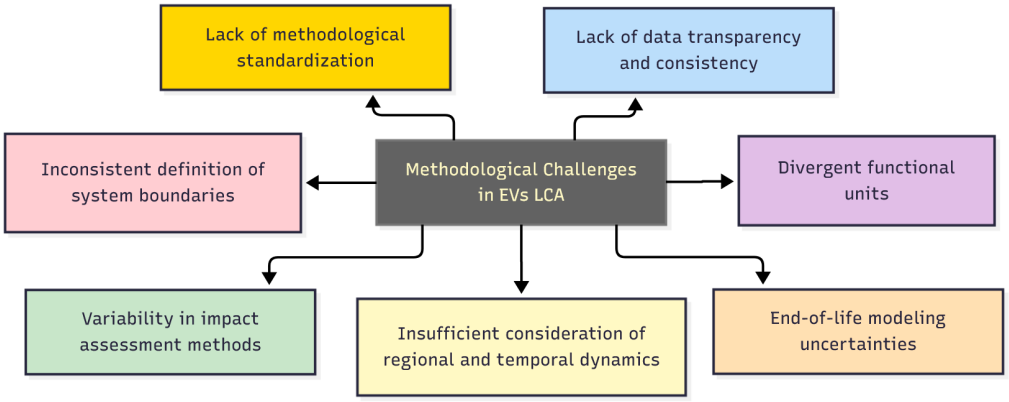


Figure 6. Key methodological challenges in LCA studies of electric vehicles. Source: Own elaboration.

One of the most critical issues is the variation in system boundaries across studies. Some LCAs adopt a cradle-to-gate approach, considering only the production phase, while others use cradle-to-grave, including use and end-of-life stages. Certain analyses exclude important phases such as battery recycling or vehicle maintenance, which can significantly alter results. The lack of a standardized system boundary definition limits the comparability of studies and weakens the consistency of conclusions drawn across the literature.

In Table 2 various types of batteries and different approaches to life cycle assessment (LCA) are presented.

Table 2. Summary of Electric Vehicle Batteries by Chemistry and LCA Approach.

Battery Chemistry	LCA Approach	Reference
Lithium-ion batteries (LIBs)	cradle-to-cradle	Chen et al. [62]
Lithium-ion battery (NCM811)	cradle-to-cradle	Wu et al. [63]
Lithium-ion battery from water-based	cradle-to-grave	Shen et al. [97]
Lithium nickel cobalt manganese oxide (NCM) and lithium iron phosphate (LFP)	cradle-to-grave	Feng et al. [57]
Lithium iron phosphate ($LiFePO_4$) and lithium manganese oxide ($LiMn_2O_4$)	cradle-to-grave	Marques et al. [58]
Li-Sulphur and Li-ion: Nickel-Cobalt-Manganese (NCM)	cradle-to-grave	Benveniste et al. [59]
Lithium-ion, sodium-ion, and solid-state battery (LIB, SIB, and SSB)	cradle-to-gate	Degen et al. [60]
Silicon Nanowire (NMC-SiNW) and Silicon Nanotube (NMC-SiNT) Based Lithium Ion Batteries	cradle-to-gate	Wang et al. [61]

Source: Own elaboration based on literature.

Despite the growing importance of LCA in evaluating electric vehicles, there is no universally accepted methodological framework or industry standard guiding how such assessments should be conducted. The lack of standardized guidelines leads to divergent practices across academia, industry, and policy-focused studies. Wong et al. [98] emphasized the need for clearer disclosure of Product Carbon Footprint (PCF) methodologies by manufacturers, allowing for meaningful comparisons.

Many studies use different data sources and assumptions regarding energy use, material composition, and emissions factors. In some cases, data are outdated or based on secondary estimates, leading to considerable uncertainty. Moreover, regional specificity is often lacking. Studies fail to reflect local grid mixes, manufacturing processes, or climatic conditions, all of which significantly influence the environmental footprint of EVs.

Functional units, which define the basis of comparison in LCA, vary substantially between studies, ranging from "per vehicle produced" to "per kilometer driven" or "per passenger-kilometer." This inconsistency directly affects how environmental impacts are calculated and interpreted. For example, a study measuring impact per km may favor smaller vehicles, while one using per vehicle may mask differences in usage efficiency. The absence of harmonized functional units reduces the utility of LCA results for decision-makers.

There is no uniformity in how environmental impacts are quantified across studies. Some analyses focus solely on greenhouse gas emissions, while others include a broader range of categories such as resource depletion, human toxicity, water use, and land occupation. Different impact assessment frameworks (e.g., ReCiPe, ILCD, CML) yield differing results even for similar data inputs. This methodological variability further complicates the comparison of findings across studies.

Few studies adequately account for regional differences in electricity generation, which significantly affect the carbon intensity of the use phase. Additionally, most LCAs treat the energy mix as static, failing to model likely decarbonization scenarios. This leads to results that may not reflect future conditions or regional realities, reducing the predictive value of the assessments.

The end-of-life phase, particularly the treatment and recycling of batteries, remains highly uncertain. Recycling technologies and efficiencies vary widely, and there is limited consensus on how to model second-life applications. Some studies adopt a cut-off approach, while others use allocation methods, further contributing to inconsistency in reported outcomes.

These methodological challenges collectively hinder the comparability and credibility of LCA results in the EV sector. Addressing them requires greater transparency in reporting, more rigorous data harmonization, and the development of standardized methodological frameworks. Such efforts would improve the robustness of environmental assessments and support more informed policy and investment decisions in sustainable mobility.

4. Discussion

4.1. Thematic Clusters in EV LCA Research

The bibliometric analysis maps the research landscape of EV-related LCA, revealing four main thematic clusters. Methodological and technological aspects of LCA dominate one cluster, while system-level assessments of EV production, use, and recycling form another. A third cluster highlights technical investigations into battery chemistries, materials, and resource sustainability, whereas the fourth centers on emissions, greenhouse gases, and comparative evaluations with conventional vehicles. Together, these clusters illustrate how the field integrates methodological development, system-wide sustainability assessment,

material-level analysis, and emissions-focused comparisons, thereby mapping both the breadth and depth of current EV LCA research.

4.2. Comparative Environmental Impacts of EVs and ICEVs

Comparative LCA studies consistently highlight that while electric vehicles (EVs) outperform internal combustion engine vehicles (ICEVs) in terms of greenhouse gas emissions and fossil fuel use, their overall sustainability depends heavily on regional electricity mixes, driving patterns, and assumptions about vehicle lifespan. EV production, particularly battery manufacturing, remains highly carbon-intensive, often offsetting part of the benefits of the use phase. In coal-dependent grids, EVs may show limited or even negative advantages over ICEVs. Nevertheless, as electricity decarbonizes and battery technologies advance, EVs demonstrate clear long-term environmental benefits, with additional gains achievable through second-life applications, recycling, and eco-design strategies. Plug-in hybrid vehicles (PHEVs) emerge as transitional solutions in some contexts, while fuel cell vehicles (FCEVs) show strong potential when powered by low-carbon hydrogen. Overall, the literature emphasizes the importance of system-level considerations, encompassing energy infrastructure, manufacturing, and vehicle use, in determining the actual environmental benefits of electrification.

4.3. Battery Production and Emerging Technologies

Life cycle assessments consistently show that battery production remains the most environmentally intensive stage of EV life cycles, largely driven by energy- and material-intensive cathode manufacturing. Recycling, cascading use, and second-life applications offer substantial mitigation potential, with hydrometallurgical processes often delivering the greatest reductions in emissions. Comparative studies of battery chemistries reveal that while LFP designs generally perform better in terms of operational efficiency and durability, NCM and other high-energy chemistries provide higher recycling value. Emerging technologies, such as Li–S, Li–O_2, solid-state, sodium-ion, and silicon-based batteries, show promise for reducing resource depletion and greenhouse gas emissions, although their environmental benefits are highly dependent on design choices, manufacturing methods, and lifetime performance. At the system level, advances in water-based manufacturing, thermal management, and optimized fleet integration can further reduce environmental burdens. Finally, the overall sustainability of EVs depends strongly on contextual factors such as electricity mix, charging strategies, and regional energy infrastructure. Together, these findings emphasize that reducing the environmental footprint of EV batteries requires a dual focus: accelerating technological innovation in battery chemistries and production, while simultaneously implementing effective recycling, energy decarbonization, and system-level optimization strategies.

4.4. Regional Differences and Grid Dependency

Regional and country-specific LCAs demonstrate that the sustainability of EVs is highly dependent on local conditions, with the electricity mix emerging as the most decisive factor. Clean, renewable-based grids, such as those in Norway, Quebec, or France, enable substantial reductions in greenhouse gas emissions, whereas fossil-fuel-dominated grids, as seen in China, Alberta, or Indonesia, can offset or even negate these potential benefits. The future decarbonization of power systems consistently amplifies the environmental benefits of EV adoption, underscoring the need to align electrification strategies with the expansion of renewable energy. Moreover, regional studies emphasize the importance of context-sensitive approaches, including shared mobility systems, second-life battery applications, and smart charging strategies aligned with low-carbon supply chains. Overall, while EVs generally outperform conventional vehicles and often hydrogen alternatives,

their true sustainability depends on integrating technological advances with regionally tailored energy and transport policies.

4.5. Strategies for Reducing Environmental Impacts

Researchers have identified a range of strategies to reduce the environmental impacts of EVs across their life cycle. Advancements in battery chemistries and manufacturing methods, such as solvent-free electrode processing, demonstrate substantial reductions in energy use and greenhouse gas emissions compared to conventional techniques. Recycling and second-life applications play a central role, with hydrometallurgical and direct recycling approaches significantly reducing CO_2 emissions compared to virgin material production and offering additional benefits when combined in closed-loop systems. Improvements in thermal management, particularly passive battery cooling systems, also contribute to reduced environmental burdens. On the use-phase side, integrating renewable energy into both vehicle production and charging, alongside smart charging strategies, can markedly reduce emissions by aligning electricity demand with low-carbon supply. Together, these findings highlight that targeted innovations in battery design, recycling technologies, thermal management, and energy supply are crucial for enhancing the sustainability of EVs.

4.6. Suggestions for Standardization of Future LCA Methods

To enhance comparability across LCA studies of electric vehicles, greater efforts are needed to harmonize both system boundary definitions and functional units. A unified system boundary should ideally adopt a cradle-to-grave perspective, encompassing the entire life cycle of the vehicle, including raw material extraction, manufacturing (including battery production), use phase (with region-specific energy mixes), and end-of-life treatment or recycling. This comprehensive boundary ensures that environmental trade-offs across life stages are properly captured and avoids misleading conclusions that may arise from partial assessments.

In terms of functional units, standardization is equally critical. While studies currently use a variety of units, such as per vehicle, per kilometer driven, or per passenger-kilometer, a commonly accepted unit like "per vehicle-kilometer traveled" under specified driving and usage conditions may offer a more balanced basis for comparison. Functional units should also reflect vehicle class, battery size, and driving patterns to ensure realistic and context-specific interpretations.

In line with best practices, future LCA studies should clearly justify their choice of functional unit and system boundaries and, where possible, provide parallel calculations using multiple functional units to facilitate cross-study comparison. Establishing standardized guidelines, perhaps under international LCA frameworks such as ISO 14040/44 or through sector-specific collaborations, would significantly improve the methodological coherence of this research domain.

5. Conclusions

This study provides a comprehensive overview of life-cycle assessments (LCA) applied to electric vehicles (EVs), highlighting both prevailing research trends and methodological challenges. Key factors influencing environmental outcomes, such as battery production, electricity mix, and recycling practices, were identified. Variations in system boundaries, functional units, and data sources were also shown to affect comparability across studies. The findings underscore the importance of considering regional energy contexts and methodological consistency to ensure accurate, policy-relevant assessments, offering guidance for future research and sustainable electrification strategies.

The bibliometric and comparative LCA analyses indicate that electric vehicles (EVs) offer substantial environmental benefits over conventional internal combustion engine vehicles (ICEVs), particularly in terms of greenhouse gas emissions and fossil fuel use. However, these benefits are strongly influenced by regional electricity mixes, driving patterns, and assumptions about vehicle lifespan. Battery production remains the most environmentally intensive stage, yet recycling, second-life applications, and advances in battery chemistries can significantly mitigate these impacts. Emerging technologies, system-level optimizations, and integration of renewable energy further enhance EV sustainability. Regional and country-specific studies highlight that clean electricity grids are crucial for maximizing environmental benefits, while fossil-fuel-dominated grids may limit or offset these gains. Overall, improving the sustainability of EVs requires a dual approach: advancing battery and vehicle technologies while implementing energy decarbonization, recycling strategies, and context-sensitive policies. In conclusion, the findings of this review contribute to advancing both the methodological rigor and practical applicability of LCAs, offering valuable insights for future research and sustainable mobility policies.

Despite the comprehensive scope of this review, certain limitations should be acknowledged. First, the analysis was restricted to studies indexed in the Scopus database, which may exclude relevant research published elsewhere. Second, the heterogeneity of LCA methodologies and reporting standards limited the comparability of results across studies. Moreover, rapidly evolving battery chemistries, recycling technologies, and regional electricity mixes mean that some findings may become outdated as new data emerge.

One of the limitations of this review lies in the decision to restrict the initial literature search to titles only, which may have led to the omission of some relevant studies. This approach was adopted based on a preliminary analysis indicating that broader searches (e.g., title–abstract–keywords) produced a high number of results unrelated to the core topic, thereby increasing the risk of subjectivity and reducing review efficiency. While this narrower search strategy improved the topical relevance of included studies, it inevitably limited the scope. To mitigate this, a snowballing technique was applied to identify additional key sources. The review thus prioritizes depth and precision over exhaustive coverage, aiming to offer a focused synthesis of the most directly relevant literature.

We also acknowledge that rapid advancements in battery technology and evolving regional power structures pose challenges for ensuring the timeliness of data used in LCA studies. While this review primarily synthesizes existing literature up to the most recent studies available, we highlight these dynamic factors as key sources of uncertainty and variability in the results. Additionally, we emphasize the need for future research to continuously update datasets and consider emerging technologies and regional energy transitions to maintain the relevance and accuracy of LCAs.

The rapid evolution of battery technologies, particularly the development of solid-state batteries (SSBs) and other next-generation chemistries, introduces both opportunities and challenges for the environmental sustainability of electric vehicles. Solid-state batteries are characterized by the use of solid electrolytes, which enhance safety and allow for higher energy density compared with conventional lithium-ion batteries. These improvements can potentially extend driving range, reduce material intensity per unit of energy stored, and improve overall life-cycle performance.

However, the production of SSBs may also involve new materials (e.g., lithium metal, sulfide-or oxide-based electrolytes) and complex manufacturing processes, which can lead to additional environmental burdens during extraction, synthesis, and end-of-life management. The environmental trade-offs of these technologies remain uncertain due to limited industrial-scale data and the lack of standardized LCA models for emerging chemistries.

To ensure reliable sustainability assessments, future LCA studies should adopt a prospective or scenario-based approach that accounts for technological learning curves, material supply dynamics, and recycling innovations. Integrating dynamic life-cycle modeling with techno-economic and material flow analyses could also improve the predictive accuracy of environmental performance estimates. Such efforts are crucial to guide policy and investment decisions toward the most sustainable battery technologies and to avoid unintended environmental consequences during the transition to advanced energy storage systems.

Despite the promising strategies identified for reducing the environmental impacts of electric vehicles, several practical challenges must be addressed to fully realize their potential. While strategies such as smart charging and battery recycling offer significant potential to reduce the environmental footprint of electric vehicles, their practical implementation faces several challenges.

Smart charging, which optimizes the timing and rate of EV charging to align with renewable energy availability and grid capacity, requires advanced infrastructure, including widespread deployment of smart meters, communication technologies, and real-time data management systems. Additionally, regulatory and market frameworks must be adapted to incentivize flexible charging behaviors among consumers. Without coordinated policy support and consumer engagement, the full environmental benefits of smart charging may not be realized. To address these challenges, investments in grid modernization, development of dynamic pricing schemes, and targeted educational campaigns are essential.

Battery recycling faces hurdles related to collection logistics, variability in battery chemistries, and the economic viability of recovery processes. Efficient collection systems must be established to gather end-of-life batteries from diverse sources, while recycling technologies need to be adaptable to different battery designs and materials to maximize resource recovery. Moreover, current recycling methods may not fully recover all valuable materials, limiting environmental gains. Policy incentives, such as extended producer responsibility and subsidies for recycling infrastructure, alongside continued research into advanced recycling technologies (e.g., hydrometallurgical and direct recycling methods), are critical to overcoming these barriers.

Addressing these practical challenges through coordinated technological, economic, and policy measures is crucial to realizing the potential environmental benefits of EV strategies and supporting the transition to sustainable electric mobility.

Future research should focus on developing integrated methodological frameworks for EV LCAs. Particular attention should be paid to system boundary definitions, functional units, and data transparency. Further studies are also needed to assess next-generation battery technologies, dynamic electricity mix scenarios, and end-of-life management strategies under real-world conditions. Strengthening interdisciplinary collaboration and integrating LCA with techno-economic and social impact assessments will be critical for supporting evidence-based policymaking in sustainable mobility.

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