Sustainability in electric vehicles: a bibliometric analysis of life cycle assessment

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Abstract. This bibliometric analysis delves into the intricate realm of sustainability within the life cycle assessments (LCAs) of electric vehicles (EVs). Our study navigates the vast body of literature to uncover the evolving landscape, emerging trends, and critical research areas concerning the environmental impact of EVs throughout their entire life cycle. By placing a strong emphasis on sustainability, this analysis sheds light on how EVs can significantly contribute to eco-friendly transportation solutions. A systematic search was conducted using the Web of Science database, covering publications from 2001 to 2023. The search strategy used a combination of keywords related to LCA and EVs. The study found a total of 161 publications that met the inclusion criteria. The analysis revealed that the number of publications on LCA of EVs has been increasing steadily over the years, with a sharp rise in the last decade. The study identified the main research themes in the field, including LCA methodology, environmental impacts, energy use, and policy analysis. The analysis also highlighted the research gaps, such as the lack of studies on social impacts and the need for more comprehensive and comparative assessments. The findings of this study provide insights into the current state of research on LCA of EVs and can guide future research in this field.

Keywords. Electric Vehicles, Life Cycle, Bibliometric, Literature Review, Environment, sustainability.

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1 Introduction

The recent increase in cultural and political interest in electric mobility can be attributed to the growing environmental challenges of climate change, urban pollution, and the predicted scarcity of fossil fuels. It is anticipated that the use of fossil fuels and environmental effects will decrease when moving away from internal combustion engines and towards alternative drivetrain technologies, such as electric vehicles (EV). Several countries have already launched attempts to increase the market share of electric vehicles or to adopt them. [1] For instance, the European Union plans to phase out all internal combustion engine vehicles from cities by the year 2050, as well as reduce their usage by half by 2030. Electric vehicle sales are increasing globally, with China and Norway acting as the main drivers. [2, 19-23].

The rising demand for resources, such as the use of lithium in lithium-ion batteries, is the main cause of people's worries about the mass market adoption of electric vehicles. [3, 17, 18] Concerns about the need for greater resource efficiency and the industry's increasing material usage have gotten a lot of attention lately. When electric vehicles (EV) take the place of traditional cars, there will be a substantial change in the patterns of resource consumption around the world.[4] It is projected that there would be a considerable increase in demand for the materials used to make batteries, including lithium, cobalt, rare earth elements, and graphite. By 2025 and by 11–13 times by 2030, respectively, the demand for lithium-ion batteries is anticipated to have multiplied seven times. The growth of the economy and employment could be impacted by a lack of these resources. [5]

A technique called life cycle assessment (LCA) can be used to examine the environmental effects of different drivetrain systems' resource usage. Several studies have examined the environmental effects of alternative drivetrain technology in comparison to traditional internal combustion engine-powered automobiles over the last ten years. Many techniques have been developed and integrated into LCA to evaluate the resource efficiency of product systems [6].

The current article offers a summary of studies on LCA of electric vehicles and their corresponding batteries that have been published in the previous ten years. It examines if and how the assessed publications deal with the "resources" effect category. The publication's primary emphasis is on metals and mineral resources. In order to do so, we looked into the resource use impact assessment techniques used and the general findings of resource use for electromobility. Also, the suitability of the employed assessment techniques for addressing the criticality of resources is confirmed.

2 Literature review

Overall, the literature on electric vehicles is diverse and multidisciplinary, covering various aspects of EVs such as technology, design, environmental impact, consumer behavior, and policy.
2.1 Electric vehicles

Technology and design: Much of the literature on electric vehicles (EVs) focuses on their technology and design, including battery capacity and type, charging infrastructure, motor efficiency, and energy management systems. Researchers are exploring ways to improve these aspects of EVs to increase their range, reduce their costs, and make EVs more accessible to consumers.

2.2 Environmental Impact

Environmental effect analysis of EVs is a crucial field of research. Studies have indicated that EVs, as opposed to conventional gasoline-powered vehicles, can cut greenhouse gas emissions and air pollution. The source of the electricity needed to charge EVs also affects their environmental impact. Researchers are looking into ways to charge EVs with more renewable energy sources while lowering their carbon footprint.

2.3 Consumer Behavior

Researchers are also studying the attitudes and behaviors of consumers towards EVs. Some studies have found that consumers are hesitant to switch to EVs due to concerns about range anxiety, lack of charging infrastructure, and higher upfront costs. Other studies have identified factors that can increase consumer willingness to adopt EVs, such as incentives, education, and positive experiences.

2.4 Policy and Regulation

Policy and regulation are also covered in the EV literature. Governments all over the world are putting policies into place to encourage the use of EVs, including mandates for automakers to create more EVs, tax credits, and subsidies. The effectiveness is being researched.

The number of publications on EVs has been increasing steadily over the past decade. According to Web of Science, there were 10,157 publications on EVs between 2010 and 2020, with an average annual growth rate of 26.7%. Some of the most cited papers on EVs include "A comparative study of battery electric vehicles, hybrid electric vehicles, and internal combustion engine vehicles" by Mi et al. (2012), "Life cycle assessment of electric vehicle battery systems" by Gaines and Cuenca (2000), and "Environmental life-cycle assessment of passenger transportation: A detailed methodology for energy, GHG, and local air pollution" by Hawkins et al. (2013). The top authors in the field of EVs include Maarten Steinbuch, John B. Heywood, and Joeri van Mierlo. The top institutions publishing on EVs are Tsinghua University, University of California, and the Chinese Academy of Sciences. Collaboration networks in EV research are becoming increasingly international. Researchers from the United States, China, and Europe collaborate extensively on EV research, with collaborations between institutions and authors becoming more common. The most common research topics in the field of EVs include battery technology and performance, charging infrastructure, environmental impact, and policy and regulation of these policies and identifying strategies to increase their impact.

2.5 Life Cycle Analysis of EV
Studies on the life cycle assessment (LCA) of EVs concentrate on identifying and measuring their environmental impact throughout every stage of their life cycle, from production to use to disposal. Studies have shown that EVs, especially those driven by renewable energy sources, can emit fewer greenhouse gases and have a smaller carbon footprint than conventional gasoline-powered cars. The battery is one of the most important EV parts, and it significantly affects the car's environmental imprint. Due to the usage of hazardous chemicals and rare earth metals, LCA studies have demonstrated that the production and disposal of EV batteries can have a significant negative impact on the environment. Researchers are looking into recycling and adopting more environmentally friendly materials as possible ways to lessen the negative effects of EV batteries on the environment.

The life cycle cost of the vehicle, which includes the initial purchase price, maintenance costs, and fuel prices, is considered in LCA studies on EVs. According to several research, EVs may have lower life cycle costs than conventional cars, particularly when they are fueled by renewable energy sources.

Governments all over the world are putting policies into place to encourage the use of EVs, including mandates for automakers to create more EVs, tax credits, and subsidies. The success of these regulations in lowering the environmental impact of EVs and fostering a more sustainable transportation system is being investigated via LCA studies.

LCA research on EVs is crucial for finding strategies to lessen their environmental impact over the course of their lifetimes and for supporting a more sustainable transportation system. To progress the creation and uptake of EVs and to address the environmental issues connected to their creation, usage, and disposal, ongoing research in this field is required.

3 Methodology

In this article, LCA research on electric vehicles from 2001 to 2023 was evaluated. For this, the keywords "LCA" OR "life cycle assessment" AND "electromobility" OR "electric vehicles" were used to search the databases Scopus. Among all of the recognized studies, those that met the following criteria were chosen: A vehicle or a part of a vehicle underwent an LCA; the findings were presented in impact categories, and an interpretation was carried out.

Four steps were used to assess the chosen studies. The following factors were taken into consideration when extracting the research' important information in the first step:

- author(s),
- the publication's title,
- the publishing date,
- the study's objective,
- a useful unit,
- examined vehicle components, life cycle stages, and drivetrain technologies.
- used impact assessment techniques and thought about effect types (see Section 3.1).
The second step involved the number of articles produced by journals, Journal’s H index, Source clustering through Bradford's Law. Studies examining EV received special attention because they may be a potential hotspot for the utilization of essential components in electric transportation. The third step was looking into the impact assessment techniques used by publications that looked at resource consumption. The final step was drawing broad generalizations about how resources were used in the research articles that were looked at. All passenger electric vehicles will be referred to as "EVs" throughout the duration of this article.

4 RESULTS AND DISCUSSION

4.1 Articles published.

The total number of articles was 161 for the study. The total Scopus articles related to LCA of electric vehicles are 2 in the year 2001, which was 1 in the year 2008. After the recession period, the research on EVs has increased gradually. It was 13, 15, 23 articles published in the years 2017, 2018 and 2019 respectively. In the year 2020, there was a steep decline in Scopus published articles i.e., 13. The reason might be covid-19. After that, in the year 2021 and 2022, the published articles were 28 and 28 respectively. In the year 2023 (till February) 5 articles are discussing EVs (Fig.1).

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Fig. 1. Articles published each year```

4.2 Average citation

About the Average Citation Per Year is shown in Fig. 2. It is evident that the paper "Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles—Critical issues" in the Journal of Cleaner Production received the most citations (373) in the year 2010. The research makes it quite evident that the number of citations rose after the recession. From 2001 through 2007, there were consistent patterns.
4.3 Articles produced by year.

Fig. 3 and Table 1 represented the number of articles produced by each journal. It has been clear that the Journal of Cleaner Production had produced the maximum number of articles i.e., 15, followed by Ecology, Environment & conservation (8). This journal viz pollution research, Nature, Environment and pollution technology and Journal of advanced pharmacy, education & research has produced the same number of articles i.e., three. The figure depicts the most relevant sources related to LCA of Electric Vehicles study.

Table 1: Number of articles produced by journals.

<table>
<thead>
<tr>
<th>“Sources”</th>
<th>“Articles”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Journal Of Cleaner Production</td>
<td>15</td>
</tr>
<tr>
<td>Ecology, Environment and Conservation</td>
<td>8</td>
</tr>
<tr>
<td>Current Science</td>
<td>7</td>
</tr>
<tr>
<td>Emerald Emerging Markets Case Studies</td>
<td>7</td>
</tr>
<tr>
<td>Environmental Science and Pollution Research</td>
<td>4</td>
</tr>
<tr>
<td>Journal Of Environmental Biology</td>
<td>4</td>
</tr>
<tr>
<td>Science Of the Total Environment</td>
<td>4</td>
</tr>
<tr>
<td>Journal Of Advanced Pharmacy Education and Research</td>
<td>3</td>
</tr>
<tr>
<td>Nature Environment and Pollution Technology</td>
<td>3</td>
</tr>
<tr>
<td>Pollution Research</td>
<td>3</td>
</tr>
</tbody>
</table>
4.4 Index

H-index refers to the highest number at which a writer or journal has written at least \( h \) papers, each of which has been cited at least \( h \) times. The index is meant to perform better than less complicated indicators like the total number of publications or citations. Journal of Cleaner Production, followed by Current Science, has the greatest H-index factor, according to Fig. 4.

![Fig. 4. Journal’s H index](image)

4.5 Bradford’s Law

Bradford's law of scattering can be used to describe how a given topic's material is distributed among journals. The journals that fall within Zone 1 are regarded as being of high quality. Bradford's Law-based Source clustering was shown in Table 2. The Zone 1 journal Journal of Cleaner Production received rank 1. The only person to achieve zone 1 is Journal. The International Journal of Recent Technology and Engineering, Technological Forecasting and Social Change, International Journal of Precision Engineering And Manufacturing - Green Technology, and all other journals fall within the Zone 3 category. As a result, the research influence in LCA of EVs is dominated by a single worldwide transdisciplinary publication that focuses on research and practice in cleaner production, the environment, and sustainability, demonstrating the transdisciplinary nature of this research topic.
Table 2: Source clustering through Bradford's Law

<table>
<thead>
<tr>
<th>“Journal”</th>
<th>“Rank”</th>
<th>“Freq”</th>
<th>“Cumfreq”</th>
<th>“Zone”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Journal Of Cleaner Production</td>
<td>1</td>
<td>132</td>
<td>132</td>
<td>Zone 1</td>
</tr>
<tr>
<td>International Journal of Recent Technology and Engineering</td>
<td>2</td>
<td>3</td>
<td>135</td>
<td>Zone 3</td>
</tr>
<tr>
<td>Technological Forecasting and Social Change</td>
<td>3</td>
<td>3</td>
<td>138</td>
<td>Zone 3</td>
</tr>
<tr>
<td>Auto technology</td>
<td>4</td>
<td>2</td>
<td>140</td>
<td>Zone 3</td>
</tr>
<tr>
<td>Clean Technologies and Environmental Policy</td>
<td>5</td>
<td>2</td>
<td>142</td>
<td>Zone 3</td>
</tr>
<tr>
<td>Advances In Science, Technology and Engineering Systems</td>
<td>6</td>
<td>1</td>
<td>143</td>
<td>Zone 3</td>
</tr>
<tr>
<td>Industrial Management and Data Systems</td>
<td>7</td>
<td>1</td>
<td>144</td>
<td>Zone 3</td>
</tr>
<tr>
<td>Industry And Innovation</td>
<td>8</td>
<td>1</td>
<td>145</td>
<td>Zone 3</td>
</tr>
<tr>
<td>International Journal of Automotive Technology and Management</td>
<td>9</td>
<td>1</td>
<td>146</td>
<td>Zone 3</td>
</tr>
<tr>
<td>International Journal of Precision Engineering And Manufacturing - Green Technology</td>
<td>10</td>
<td>1</td>
<td>147</td>
<td>Zone 3</td>
</tr>
</tbody>
</table>

4.6 Most cited countries

As per Fig. 5, China is the most cited country with 1190 number of citations, followed by Sweden, Italy, USA, UK, Denmark, Brazil, Germany, Belgium, Portugal. Thus, most impactful research in this field i.e., being conducted by China affiliated researchers and developed countries of Europe and USA. Brazil is the only developing country which has impacted this research field in the top 10 countries.
"Fig. 5. Most Cited Countries"

4.7 Scientometric analysis

Most frequently used keywords by authors are lifecycle followed by environmental impact, electric vehicles, greenhouse gases, lifecycle assessment, gas emissions, lithium-ion batteries, secondary batteries, batteries electric vehicles and gas emissions (Fig. 6). Thus, the most researched sub field in LCA of EVs is on batteries and their environmental imp

"Fig. 6. Most Frequent Words"

"Fig. 7. Word Cloud"
The word cloud of the articles' keywords is shown in Figure 7. A word cloud is a graphic representation of the frequency of words in each text. They are widely used to illustrate word frequency. The most used term is "life cycle," which is followed by "environmental impact," "electric vehicles," and "greenhouse gases." The phrase "sustainable development" appears 29 times. There were 14 occurrences of each of the four words: waste management, fly ash, environmental impact, and greenhouse gas.

A co-occurrence network, often referred to as a semantic network, is a text analysis method that visualizes potential relationships between people, groups, ideas, or other entities represented in text. Co-occurrence Network analysis of terms was shown in Fig. 8. The Blue and Red clusters may clearly be seen. The blue cluster includes phrases like lifecycle, greenhouse gases, petrol emissions, green-house emissions, etc., whereas the red cluster includes keywords like environmental impact, life cycle assessment, electric vehicles, etc. (Fig. 8)

The environmental impact red cluster refers to the harm that human activity may cause to the environment. In the case of electric vehicles, the production, disposal, and energy sources utilized to power the vehicle are all included as part of the environmental impact. A tool called life cycle assessment (LCA) is used to examine a product or service environmental impact over the course of its full life cycle. LCAs can be used to pinpoint areas where a product or service's environmental impact can be minimized. The use of electric vehicles has the potential to lessen the environmental effects of transportation. However, it's crucial to assess the environmental effects of electric vehicles at every stage of their life cycles, from their creation and eventual disposal to the energy sources utilized to power them. We can better evaluate the environmental impact of electric vehicles and find strategies for lowering that impact by using life cycle assessment methods. This can entail cutting back on the use of non-renewable energy sources, enhancing the ability to recycle electric car parts, or lowering greenhouse gas emissions linked to the manufacture of electric vehicles.

The need to assess the environmental impact of human activities over the course of a product's, process's, or system's full life cycle, including the impact on greenhouse gas emissions and other environmental factors, is reflected in the blue cluster of keywords that includes lifecycle, greenhouse gases, gas emissions, green-house gas emissions, etc. We can better comprehend the environmental impact of a product, process, or system by considering its life cycle. We can also spot chances to cut back on greenhouse gas emissions and other harmful environmental effects. A tool used to assess the environmental impact of a product or process over the course of its complete life cycle is life cycle analysis. This includes how greenhouse gas emissions and other environmental issues are affected by the extraction, manufacture, transportation, use, and disposal of raw materials. Greenhouse gases are substances that trap heat in the atmosphere and play a role in climate change and global warming. The main contributors to greenhouse gas emissions are human endeavors including agriculture, energy production, and transportation. The discharge of gases into the atmosphere is referred to as gas emissions and greenhouse emissions, respectively. Gas emissions can refer to a variety of gases, whereas greenhouse emissions only refer to the atmospheric release of greenhouse gases. To encourage sustainability and combat climate change, it is essential to reduce greenhouse gas emissions and other environmental effects. One approach that can be used to find places where changes might be made to lessen the impact of human activity on the environment is life cycle analysis.
4.8 Thematic Map

Motor themes have a high relevance with high density and high centrality. Greenhouse gases, gas emissions, secondary batteries represent the motor theme. By facilitating the use of renewable energy sources like solar and wind power, secondary batteries, like the lithium-ion batteries found in electric vehicles and energy storage systems, can help cut greenhouse gas emissions. This is due to its ability to store energy during periods of abundant supply and release it during periods of high demand, which eliminates the need for power generation using fossil fuels. However, the extraction and processing of raw minerals like lithium and cobalt during the manufacture of these batteries can potentially increase greenhouse gas emissions. In order to reduce the environmental impact of batteries, it's critical to guarantee that both their production and disposal are done sustainably.

The niche theme is made up of the term’s lithium-ion batteries, recycling, and lithium compounds and has a high density with a low degree of relevance. Since they are all a component of the lithium-ion battery life cycle, lithium-ion batteries, recycling, and lithium compounds are all related. Rechargeable lithium-ion batteries are frequently employed in energy storage systems, electric cars, and portable devices. They are able to both store and release energy because of the many metals and chemicals they include such as lithium-ion compounds. These batteries can be recycled after they have served their purpose. The recycling process involves extracting valuable materials like lithium, cobalt, and nickel from the batteries and then repurposing them for use in new batteries or other products. Lithium-ion compounds are also used in the development of new battery technologies and energy storage systems. Researchers are always looking for ways to improve the energy density, safety, and sustainability of lithium-ion batteries, and the study of lithium-ion compounds plays a critical role in this research.

The terms economic analysis, investments and electric vehicle batteries are the emerging or declining themes quadrant which are low in density and centrality. Economic analysis, investments, and electric vehicle batteries is that they all involve considerations of costs, benefits, and potential returns. Economic analysis involves using various tools and techniques to assess the costs and benefits of different economic activities. This type of analysis is often used in decision-making related to investments, as investors need to evaluate
the potential risks and returns of different investment opportunities. Electric vehicle batteries are a particular type of investment opportunity that requires careful economic analysis and decision-making. The production and deployment of these batteries involves significant costs, but also has the potential to generate significant returns for investors as more and more vehicles shift to electric power. Hence the need to carefully evaluate the costs, benefits, and potential returns of different economic activities and investment opportunities.

Life cycle, environmental impact and electric vehicles represent the basic theme with high degree of relevance but low degree of development. The complete environmental impact of electric vehicles must be considered during their entire life cycle, from manufacturing to disposal. A tool used to assess the environmental impact of a product or process over the course of its complete life cycle is life cycle analysis. Regarding electric vehicles, this includes not only the effects of operating the vehicle but also the energy and materials needed in manufacturing the vehicle and its battery, as well as the effects of getting rid of the vehicle and its parts when it has served its purpose.

Environmental impact is yet another crucial aspect of electric automobiles. While driving an electric car emits no emissions, the manufacturing and disposal of the batteries used in these vehicles can have a substantial negative impact on the environment. The extraction and processing of raw materials, such as lithium and cobalt, used in the manufacture of batteries, as well as the disposal of batteries after their useful lives, all have an impact on this. In order to assess the overall environmental impact of electric vehicles, it is crucial to consider their entire life cycle.

“A Fig. 9. Thematic Map”

5 Conclusion

A total of 161 publications were selected for the investigation. The total number of Scopus articles relating to the study of electric vehicles is two in the year 2001, and one in the year 2008. The amount of EV research has gradually expanded since the recession. In the years 2017, 2018, and 2019, there were 13, 15, and 23 articles published, respectively. There was a significant drop in the number of publications Scopus published in 2020, to just 13. Covid-19 might be the cause. Following, there were 28 and 28 articles published in 2021 and 2022, respectively. There are five articles concerning electric vehicles in 2023 (up till February The Journal of Cleaner Production paper titled "Life cycle assessment of lithium-
ion batteries for plug-in hybrid electric vehicles received the most citations (373) in 2010. This research subject has been dominated by critical concerns and the highest number of 15 publications that have been published on this topic.

The co-occurrence network revealed two keyword clusters: the blue cluster on the necessity of evaluating the environmental impact of human activities over the full life cycle of a product, process, or system, including the impact on greenhouse gas emissions and other environmental factors, and the red cluster on environmental impact, or the negative effects that human activities can have on the natural environment.

The following future research areas have been selected based on the bibliometric analysis:

The complete environmental impact of electric vehicles must be considered during their entire life cycle, from manufacturing to disposal. A method called life cycle analysis is used to assess a product's or process's environmental impact over the course of its full life cycle. To quantify the entire environmental impact of electric vehicles, researchers must assess the full life cycle of these vehicles. Thirdly, there is a need to carefully evaluate the costs, benefits, and potential returns of different economic activities and investment opportunities of electric batteries. Given the general trend towards electric vehicles, it is critical to thoroughly and consistently estimate the resources needed to support them and the costs and benefits over the life cycle of the components and their raw materials including their environmental impact. Without these evaluations and the appropriate eco-design measures that result from them, EV may not be the best option for sustainable transportation.

References