Review Article

Publication Trends, Research Landscape, and Scientific Developments on Electric Vehicles Safety Research (2006–2021)

ABSTRACT

Electric vehicles (EVs) are vehicles or automobiles that utilise a single or several electric-based motors, battery packs and collector systems for propulsion. With the paradigm shift to green electricity, EVs are considered major technological innovations that could mitigate GHG emissions from transportation. Despite their potential, EVs have numerous problems ranging from thermal runaways and electric shocks to fire and explosions. Therefore, electric vehicle safety (EVS) has become an important research area with over 5,000 publications to date. Based on data from the Elsevier Scopus database, the PRISMA technique was used to critically examine the research landscape and scientific developments in EVS research from 2006 to 2021. The results revealed 220 published documents comprising conference papers, articles, reviews, and book chapters. Research landscape analysis revealed that Zhenpo Wang, Ming H. Lu and Ming U. Jen are the most prolific authors, whereas the largest funding organisation is the National Natural Science Foundation (NSFC) of China. The findings indicate that EVS research/researchers have received significant financial support and non-monetary resources, which has resulted in numerous scientific developments and published documents over the years. For example, the improvements in the safety and efficiency of Li-ion batteries, along with tackling operational problems such as thermal runaway, electric shock, explosions, and other risks associated with battery damage, are under examination. In conclusion, the study shows that the research impact and scientific developments on EVS research will continue to grow, especially with growing calls to reduce fossil fuel-based energy dependence and GHG emissions from transportation.

Keywords:Electric Vehicles, Vehicular Safety, Emissions Reduction, Climate Change, Global warming

1. INTRODUCTION

The twin challenges of global warming and climate change have become hot topics among academics, scientists, and policymakers around the world[1]. To address these challenges, humanity needs to transition from fossil fuelsto more renewable alternativesources[2]. The general consensus is that the proposed paradigm shift will require significant investmentsin innovative, efficient, and low-carbon technologies that reduce greenhouse gas (GHG) emissions and eliminatewaste[3]. According to the COP21 Paris Accord on Climate Change, the global annual anthropogenic GHG emissions must be reduced from 50 billion tonnes to zero by the year 2050[4]. Conforming to the accord's objectives, such efforts could helpslow down the planet's warming to below 1.5 °C[5], particularly in sectors such as energy, buildings, and transportation among others.

The transportation sector is a critical part of the global economy due to its role in the timely, effective, and efficient movement of people, goods, and services[6]. It is currently estimated that the transportation sector accounts for one-fifth(or 8 billion tonnes) of all global CO_2 emissions around the world. Likewise, transportation accounts for ~24% of the CO_2 emissions from energy. The sectoral breakdown shows that road vehicles (passenger and freight) account for 74.5%, whereas aviation (11.6%), shipping (10.6%), rail (1%), and others account for the remainder[7]. With the global population, incomes, and living standards set to increase, analysts posit that the demand for transportation will concurrently increase in the coming years. Therefore, it is predicted that CO_2 emissions from the transport sector will also increase significantly over the coming years, except sustainable strategies and innovative technologies are designed, developed, and implemented.

According to studies in the scientific literature, electric vehicles (EVs) are one of the significant technological innovations that could help to mitigate CO_2 and other GHGs emissions from the transportation sector.An EV is an automobile or car that usessingle or several electric-based motors for propulsion. In practice, an EV consists of a battery and collector system that autonomously powers the vehicle[8]. With the paradigm shift to green electricity, the deployment of EVs is expected to ensure the reduction or mitigation of GHG emissions from vehicles and cars[7, 9, 10]. Davis *et al.,* [9]observed that the attainment of net-zero emissions using large trucks (long-distance road freight), aviation, and shopping would be problematic. Hence, the deployment of EVs in passenger vehicles is clearly a step in the right direction of emissions reduction in the transport sector[11]. In addition, the IPCC report on transportation states that EVs have zero or low tailpipe or fuel-production emissions. In addition, EVs have an operational drive-train efficiency of ~80% when compared to conventional ICEs, which have LDVs of 20–35%[12].

Despite their potential for addressing the problems of GHG emissions, global warming, and climate change, EVs have some widely reported problems of their own [13, 14]. For example, studies have shown that the EVs currently available in the global market have an average driving range of ~130 km, require extended recharge times (i.e., 4 or more hours), and have expensive batteries[12]. Likewise, other researchers have reported problems with currently available battery technologies such as Lithium-ion (Li-ion) batteries (or LIBs),ranging from thermal runaway, explosions, electric shock among others[15-18]. Consequently, numerous studies have been carried out to propose novel, low cost, and technically efficientbattery technologies such as Li-air, Li-metal, Li-sulphur, and ultra-capacitorsso as to achieve high energy and power densities. Other researchers have examined theaspects of Li-ion batteries and their use in EVs with a view to addressing the problems that pose risks to human health, safety, and the environment at large[19-22].

Zhang *et al.,* [23]reported that although LIBs are the most widely used battery technologies for research and industrial applications, they are prone to safety issues related to thermal runaway. This has prompted extensive research on the detection and prevention of thermal runaway in LIBs using various engineering methods, from the tuning of materials to the adoption of additives through thermo-mechanical and electrical designs.Gandoman *et al.,* [24]has reported that thesafety and reliability assessment of LIBs aspects (such as failure modes, characteristic capacity, and power fade) has become a critical aspect of future LIB-based EVs design manufacture and performance. According to the study, safety and reliability studies are also essential dynamics in the lifespan of LIBs in EVs. Other areas of research that have taken centre stage include modelling the predictive control of hybrid EVs for enhanced fuel economy, emission reductions, and inter-vehicle safety [25], as well as work-related road safety and noise levels of EVs [26]. Similarly, Wu *et al.,* [27]proposed safety management strategies for EVs using Bayesian Network modelling, whereas Yiding *et al.,* [28]investigated the safety performance of LIBs in EVs under dynamic compression conditions.

Given the outlined issues, the topic of electric vehicle safety (EVS) has become an important area of research across the globe. However, no study has attempted to explicate the scientific development and research landscape of EVS, hence the need for the study. A quick search on EVS research in the world's most extensive abstracts and citation database, Elsevier Scopus, showed that 5,927 documents had been published on the topic from 1975 to the present day. The search was based on the search query ("electric vehicle*" AND "safety") AND PUBYEAR > 1974 using the TITLE-ABS-KEY search criteria for identification of documents on selected topics from the Scopus database. The results showed that a large number of published documents exist on the topic in the literature. However, it is challenging to critically and reliability scientific growth and technological developments in the field, which is the primary objective of the present paper. Therefore, this study adopts the PRISMA approach to comprehensively examine the research landscape and scientific developments on electric vehicles safety (EVS) research over the time span from 2006 to 2021. It is envisioned that the findings will provide academics, researchers, and policymakers with comprehensive insights into growth and developments on the topic.

2. METHODOLOGY

The paper aims to examine the publicationtrends, scientific landscape, andresearch advances on electric vehicles safety (EVS) research from 2006 to 2021.This time period was selected because it allows the collection of a lot of reliable and accurate data for VOSViewer data analysis. Therefore, the published documents on the topic were identified, screened, and analysed based on the data recovered from the Elsevier Scopus database using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) approach. Firstly, an appropriate search query was designed based on the title keywords "electric", "vehicles", and "safety" to help identify all the related publications. Next, the search query ((TITLE ("Electric vehicle*"AND "Safety") AND PUBYEAR > 2005 AND PUBYEAR < 2022)) was executed in the Scopus database on 1st March 2022 to retrieve all the related publications over the time span from 2006 to 2021. The fifteen-year period was selected to recover a significant number of publications, which will ensure reliable, accurate and up-to-date information on the topic. The recovered documents were subsequently screened to remove any unwanted documents. Finally, the retrieved documents that satisfied the search query requirements were analysed to examine the publication trendson the topic. The scientific landscape on EVS research was analysed using the significant stakeholders (top authors, affiliations, funding organisations, and countries) who have actively worked on EVS research and topics over the years. The top 10 most cited publications on the topic were also examined based on-screen data from the Scopus database. Lastly, the research advances on EVS research were examined based on the top 40 most cited papers, defined as publications with 10 or more citations over the 15-year span of the study.

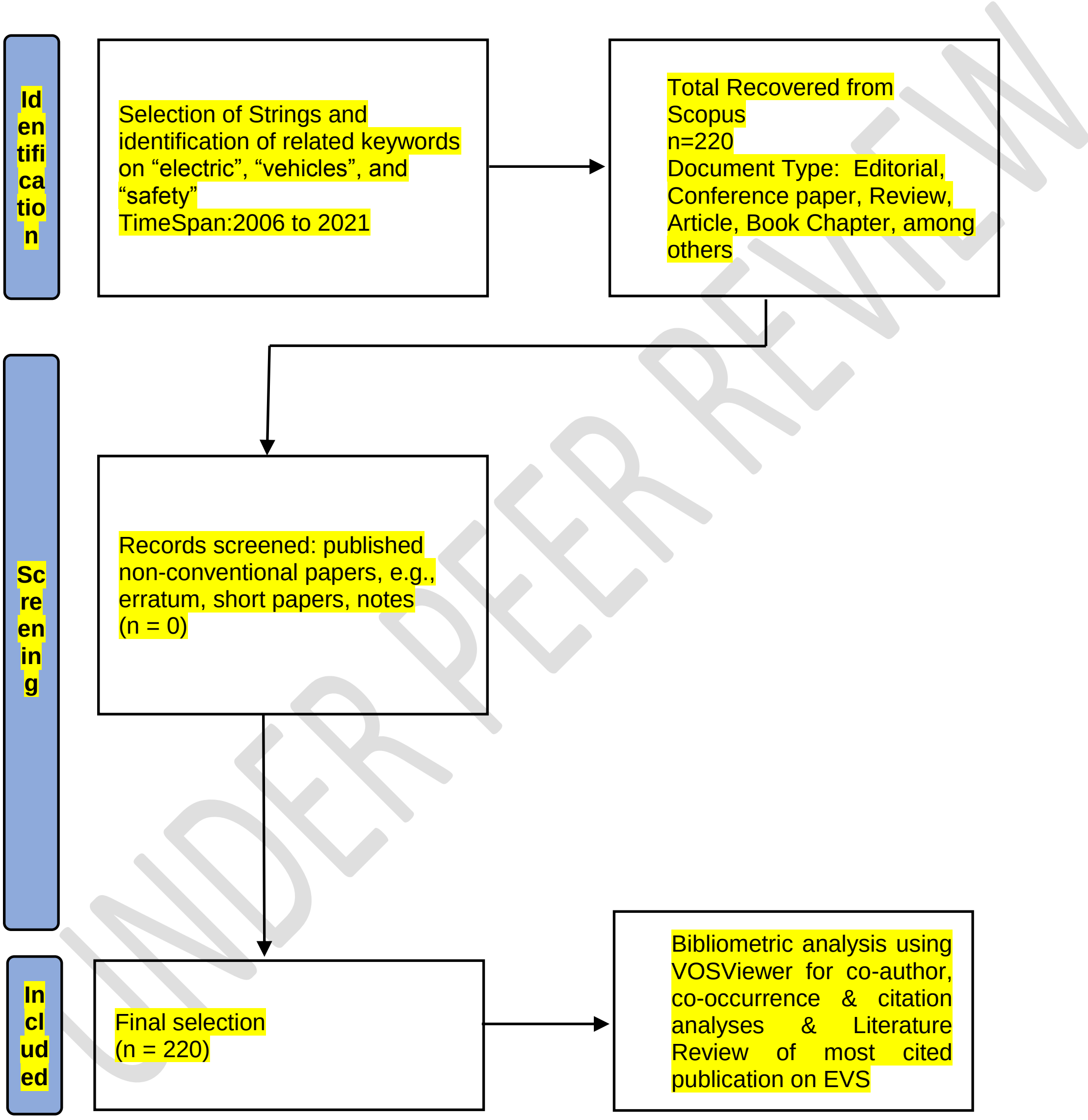

Figure1: PRISMAprocessofidentifying, screening, andanalysis.

3. RESULTS AND DISCUSSION

3.1 Publication trends analysis

The search recovered a total of 220results based on the keywords “electric vehicles” and “safety”from the Scopus database. The published documents comprise various document types, as shown in Table 1. As observed, the published documents on EVS research has been published in various formats ranging from conference papers to short surveys. The most commonly used format is the conference papers, which account for 136 publications or 61.82% of the total publications on the topic. The preference for conference papers may be due to the novelty of EVS research, which like the earliest stage or developing fields of research, typically require speedy dissemination of findings. Consequently, the traditional medium of publications, which is journal “articles”, requires rigorous peer review and lengthy periods to assess and publish the findings.

Table 1: Distribution of document types for publications on EVS Research

Document type	Total Publications (TP)	Percentage of Total (%TP)
Conference paper	136	61.82
Article	68	30.91
Review	11	5.00
Book chapter	3	1.36
Editorial	1	0.45
Short survey	1	0.45

The most commonly used conference proceedings for publications onJournal of Physics Conference Series, SAE Technical Papers and IOP Conference Series Materials Science &Engineering, whereas the journal sources are Energies and Energy. Other primarymediums of publications for EVS research, as shown in Table 1, are reviews and bookchapters. Reviews typically present an overview of the current status and future directions on any given topic of research, whereas book chapters are short presentations written by various authors who are selected or invited to contribute to a monograph or book.Further analysis on the topic shows that the number of publicationson EVS has increased over the years. As shown in Figure 2, the number of published documents increased from 2 to 37 between 2006 and 2021, which indicates scientific interest and research impact on the topic has soared over the years.

The growing interest in EVs and the safety of the technology can be ascribed to the growing global transition from fossil-based transport fuels to cleaner sources such as electric vehicles, hydrogen, and fuel cells, among others. As with novel technological developments, there are growing fears that electric vehicles, particular those with lithium-ion batteries, could place users at various risks. According to the National Transportation Safety Board (NTSB), EVs using high-voltage lithium-ion batteries are prone to fire outbreaks. In addition, the NTSB notes that fires in EVs expose human users to the risk of electric shock, uncontrolled temperature, and pressurearising from the stranded energy remaining in damaged Li-ion batteries[29]. Other studies have shown that numerous battery reignitions and thermal runaway could occur after initial fire suppression, thereby posing safety risks in high-voltage Li-ion battery fires[29].

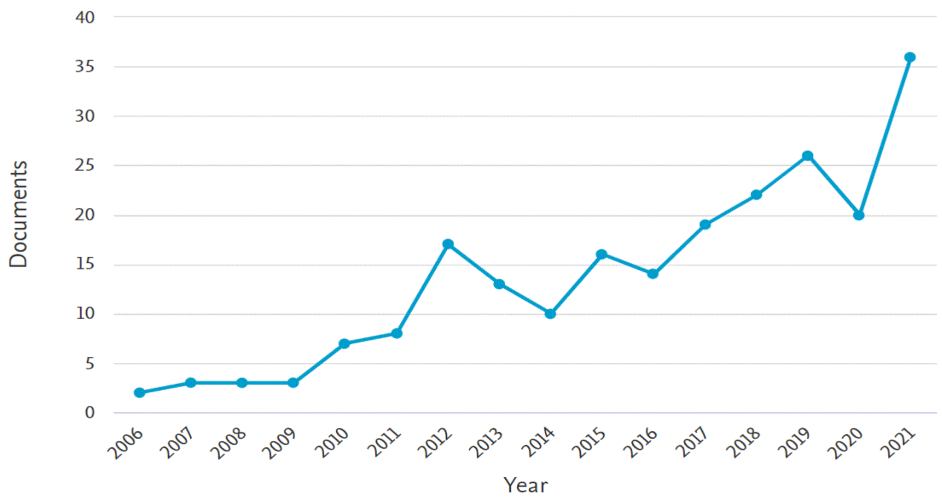

Figure 2: Publication trends on EVS Research (2006-2021)

3.2 Top authors and affiliations

The critical analysis of the top authors and affiliations can provide invaluable information on thescientific landscape and research impact on any topic.Figure presents the top 5 most active researchers on EVS research from 2006 to 2021. The top 5 most active researchers on the topic have over the years produced 3 to 5 (or 3.4 on average) published documents. Collectively, these top researchers account for 7.76% (or 17 publications) of the total publications (TP), which indicate they are the most influential on the topic. Further analysis shows that Zhenpo Wang, based at the Beijing Institute of Technology (China), has the highest number of publications (5 or 2.28% of TP) on the topic. Meanwhile, the others, namely Xingfeng Fu, Ming Une Jen, Keqiang Li, and Ming Hung Lu, each have 3 publications or collectively 5.48% of the TP. The duo of Ming Hung Lu and Ming Une Jen is based at the Industrial Technology Research Institute of Taiwan (Taiwan), whereas others are based at other affiliations. The affiliation or location of researchers plays a crucial role in their output due to access to a conducive environment, research funding, and equipment availability. Hence, the most active affiliations or research-based institutions actively investigating EVS research around the globe were analysed to examine their impact on the rate of publications on the topic.

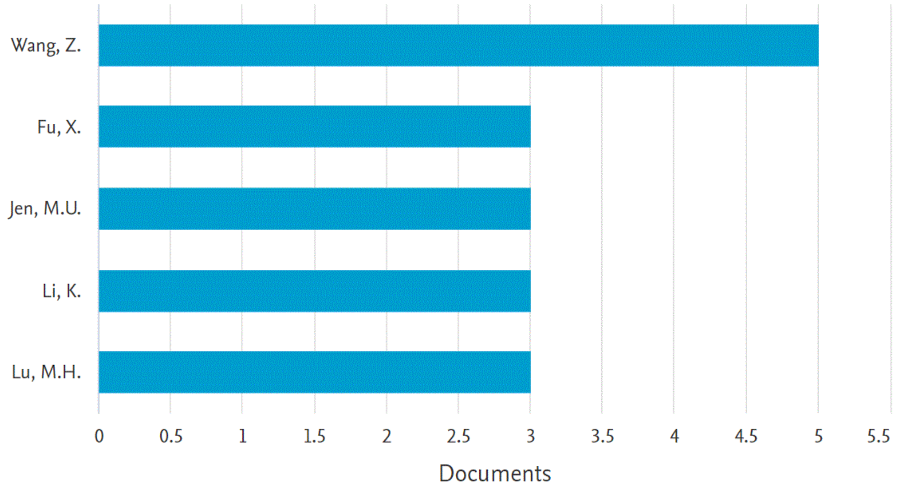

Figure 3: Top 5 most active researchers on EVS research (2006-2021)

Figure shows that the top 5 most active research affiliations on the topic have produced 6 or more published documents on the topic over the time frame examined in this study. As observed, the most active research affiliation is the Beijing Institute of Technology (China), which is the research base of Zhenpo Wang, who also has the distinction of being the most prolific researcher on the topic.

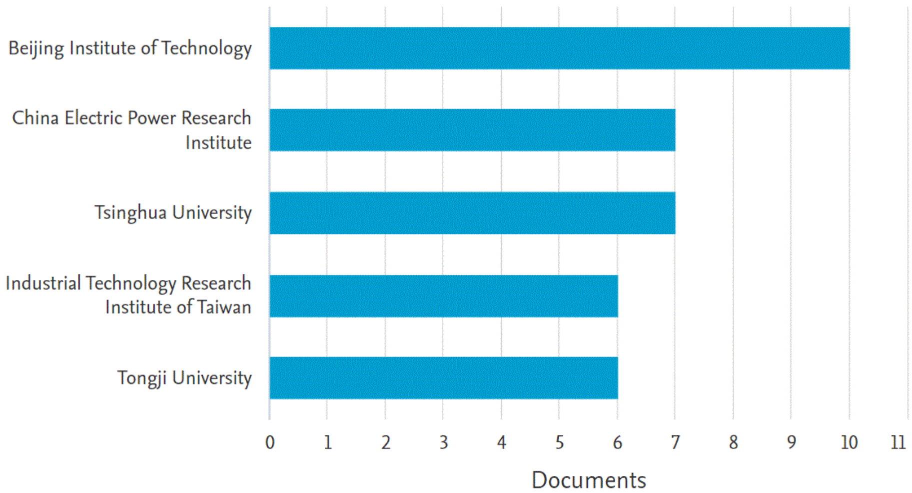

Figure 4: Top 5 most research-active affiliations on EVS research (2006-2021)

In the top 5 is also Tsinghua University (China) with 7 publications, which is mainly due to the publications of Keqiang Li. Likewise, the Industrial Technology Research Institute of Taiwan, where the duo Ming Hung Lu and Ming Une Jen are based, has produced 6 publications on EVS research over the years. The findings confirm that the location of researchers plays a crucial, if not the most singular important, role in the research productivity on the topic. Other crucial factors that influence research productivity, as earlier states, are access to financial support in the form of research funds, equipment grants, and conference/travel grants, among others.

3.3 Top funding organisations and countries

The role of financial support, usually in the form of research funds, equipment grants, and conference/travel grants is crucial to enhancing the researcher's productivity or an institution/affiliations output[30, 31]. To examine the influence of these dynamics, the role of the organisations that have funded EVS over the years was examined based on the research out of their various beneficiaries. Figure shows the top 5 funding organisations for EVS research worldwide.

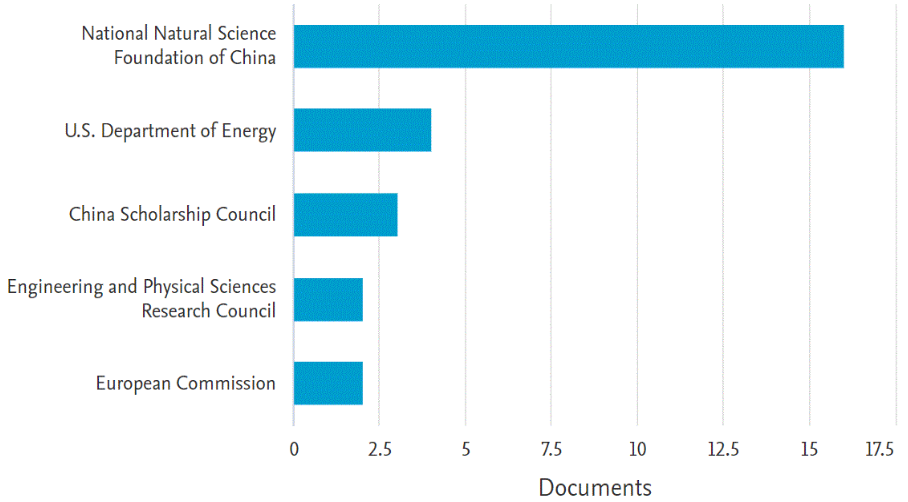

Figure 5: Top 5 funding organisations for EVS research (2006-2021)

The most active research funder is the National Natural Science Foundation (NSFC, China), with 16 published documents (or 7.31% of TP) and followed by the United States (US) Department of Energy and the China Scholarship Council with 4 and 3 publications respectively. Further analysis of the top 5 funders indicates that 2 out of the 5 top funders are based in China, whereas 2 are based in the European Commission and United Kingdom (UK) and 1 in the United States (US). The findings indicate that EV is a top priority area for researchers in China, the United States, and the EU, which may be unconnected with global efforts to reduce GHG emissions from the transport sector. One of such efforts was the ratification of the COP21 Paris Accord/Agreement on Climate Change of 2015, where nations pledged to reduce cut anthropogenic carbon dioxide (CO_2) emissions from 50 billion tonnes to zero in a bid to slow global warming by 1.5 °C[4].

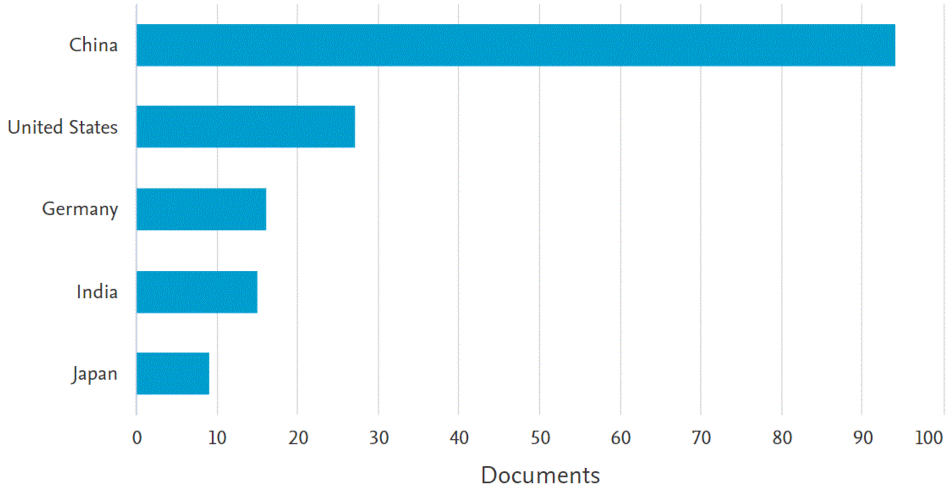

Figure 6: Top 5 research-active nations on EVS research (2006-2021)

Therefore, global environmental analysts posit that the design, development, and deployment of EVs could potentially cut transportation-related emissions, which currently account for 16.2% of non-energy GHGs worldwide[32]. According to the WEF [33], the global transportation sector is the 4th largest emitter of GHGs, accountingfor 23% of global energy-related CO_2 emissions. According to the report,the emissions from transportation arise from road vehicles (i.e., cars and trucks, 73%), planes and ships (22%), and trains (1%). Therefore, experts envisage thatthe transportation sector will play a crucial role in fulfilling the objectives ofthe Paris Agreementthrough the reduction of GHG emissions[33]. Given their roles as significant signatories to the Paris Accord, nations such as China, US, Germany, India, and Japan (see Figure) embarked on low carbon and emissions-cutting research such as electric vehicles (EVs). Such efforts continue to help tackle CO_2 and other GHGs emissions giving rise to several published documents and reports as shown in this study.

3.4 Most Cited Publications

In this study, acomprehensive analysis of the most cited paperson EVS research was performed. The data most cited publications present insights into the research growth and scientific development of any field of study. Table 2 shows an overview of the most cited publications on EVS research based on the screening criteria that eliminated articles with less than 50 citations on the topic in the Scopus database. As observed, the published documents have gained between 52 to 391 citations (or 110.89 on average) over the years examined in the study.

Table 2: Summary of the most cited publications EVS (2006-2021)

References	Title	Source title	Cited by
Rezvanizaniani *et al.*, [34]	Review and recent advances in battery health monitoring and prognostics technologies for electric vehicle (EV) safety and mobility	Journal of Power Sources	391

Belharouak *et al.,* [35]	Electrochemistry and safety of Li4Ti5O12 and graphite anodes paired with LiMn2O4 for hybrid electric vehicle Li-ion battery applications	Journal of Power Sources	123
Gandoman *et al.,* [24]	Concept of reliability and safety assessment of lithium-ion batteries in electric vehicles: Basics, progress, and challenges	Applied Energy	100
Xu *et al.,* [36]	Fully Electrified Regenerative Braking Control for Deep Energy Recovery and Maintaining Safety of Electric Vehicles	IEEE Transactions on Vehicular Technology	83
Zhang *et al.,* [23]	An Overview on Thermal Safety Issues of Lithium-ion Batteries for Electric Vehicle Application	IEEE Access	71
Lv *et al.,* [37]	Novel control algorithm of braking energy regeneration system for an electric vehicle during safety-critical driving manoeuvres	Energy Conversion and Management	61
Yuan *et al.,* [38]	Nonlinear MPC-based slip control for electric vehicles with vehicle safety constraints	Mechatronics	59
Li *et al.,* [39]	Data-Driven Safety Envelope of Lithium-Ion Batteries for Electric Vehicles	Joule	58
Zhu *et al.,* [40]	Overcharge investigation of large-format lithium-ion pouch cells with Li(Ni0.6Co0.2Mn0.2)O2 cathode for electric vehicles: Thermal runaway features and safety management method	Energy	52

The most cited publication, “Review and recent advances in battery health monitoring and prognostics technologies for electric vehicle (EV) safety and mobility”,was published in the Journal of Power Sources by Rezvanizaniani *et al.,* [34], has amassed 391 citations. Further analysis shows that the study has 3.18 times more citations than the second most cited paper, “Electrochemistry and safety of $Li_4Ti_5O_{12}$ and graphite anodes paired with $LiMn_2O_4$ for hybrid electric vehicle Li-ion battery applications” by Belharouak *et al.,* [35]. As observed, the two papers published three years apart were published in the prestigious, high impact Journal of Power Sources (Impact Factor, IF=9.127). Hence, it can be reasonably surmised that the two papers,Rezvanizaniani *et al.,* [34]and Belharouak *et al.,* [35]are the benchmark studies on EVS in the scientific literature.Other studies have also gained numerous citations by reporting on thesignificantscientific developments on EVS, as will be highlighted in section V.

3.5 Literature Review

Therisk of accidents, injury and even death from fuel, energy, and materials used in electric vehicles (EVs) has prompted research into the safety of such systems. According to various studies, EVs are typically prone to fire outbreaksand electric shocks, arising from the malfunctioning or damage to the large Li-ion batteries packs. In addition, the issues arising from thermal runway reportedly result in explosions, which pose grave risks to human health, and safety. Therefore, the safety systems to safeguard against the antecedent risks associated with EVs. For example, Arora *et al.,* [41]investigated the safety of EVs operated using Li-ion batteries. The study showed that the safety risks associated with Li-ion batteries are higher than other rechargeable battery systems such as nickel-metal hydride (NiMH). This is due to the higher energy density of Li-ion batteries, which potentially generates heat due to the chemical reactions at the electrode terminals. In addition, the organic solvent-based electrolyte present in the batteries is highly flammable, which causes ignition and evolution of extra heat on exposure to the atmosphere. The study concluded by stating the safety of such systems could be guaranteed by putting in place sufficient safeguards such as protection circuits, heat rise prevention systems, and fail-safe batteries in future EVs.

Belharouak *et al.,* [35]examined the potential safety of $Li_4Ti_5O_{12}$(LTO) and graphite anodes coupled to $LiMn_2O_4$ for application in Li-ion battery-powered EVs.The findings revealed that LTO is a promising, safe, and recyclableanode material for application in EVs. This is due to its ability to interpose Li at ~1.5 V, which indicates it has lower energy when compared to the graphite anode. In comparison, the findings also showed that the LTO anode exhibited high retention capacity, prolonged cycling, pulse impedance, calendar life as well as higher stability to thermal abuse when compared to graphite. The influence of the LiFePO4 battery pack on the in-parallel cell safety of EVs was investigated by Wang *et al.,* [42]. The safety of the battery module in EVs is dependent on the battery cell performance, but inconsistency in the arrangement could result in the uneven flow of current in the internal in-parallel battery cells. The findings showed that the safety of the battery cells during their lifecycle requires setting the safety EOC voltage based on the number of battery cells in the battery module and the applied charge of current.Zhang *et al.,* [23]reviewed the thermal safety problems associated with Li-ion batteries used to operate EVs. The authors observed that Li-ion batteries are the most sort after type of batteries sold for the manufacture of EVs. However, the batteries are prone to numerous issues ranging from thermal runaway to electric shocks, among others. As a result, the focus of global attention is focused on addressing the problems of Li-ion batteries so as to ensure the safety of EV users. The paper also highlighted the causative factors, detection, and prevention that lead to thermal runaway.Gandoman *et al.,* [24]explored the concepts of safety and reliability of Li-ion batteries, whereas Li *et al.,* [39]examined the issue of data-driven safety envelopes in EVs. According to Li *et al.,* [39]the safety of EV users is significantly compromised in the event of accidents, which necessitates the assessment of the concept of the "safety envelope". In principle, the concept of "safety envelope" in the context of EVs is defined as the range of conditions that ensure the control and safe operation of the vehicle's battery cells. According to the authors, the most significant problem associated with establishing a "safety envelope"is the procurement of datasets of tests on battery failure. Therefore, the authors proposed and developed a highly accurate computational model of Li-ion cells so as tosimulate the hazards of mechanical loading conditionsusing machine learning. The findings demonstrated that the combination of numerically generated data along with data-based simulations could effectively forecast the system safety of energy storage devices such as Li-ion in EVs. Likewise, Yiding *et al.,* [28]examined the safety characteristics of Li-ion batteries in EVs under dynamic compression settings. The findings revealed that dynamic load has a particulartoughening effect on Li-ion batteries. In addition, the study revealed that the Li-ion battery is characterised by a particular safety margin, whichbased on mechanical penetration could provide a valuable reference or safety warningin the event of mechanical abuse during future operations.

Christiaens *et al.,* [43]reported on the need for the incorporation of functional safety (FS) measures in EVs. According to the authors, FS is described asthe lack of objectionable risk caused by the failureofan electrical system, which is an essential dynamic in developing advanced vehicular systems such as EVs. As such, FS-based issues have become an essentialissue in the automobile industry resulting in the promulgation ofthe ISO 26262 functional safety standard. The results showed that the EV showed that the supervising concept satisfies the time of reaction specifications which helps to guarantee that the unintentional torque increase does not result in uncontrollable acceleration of the vehicle.Chung *et al.,* [44]proposed and developed a safety design for an EV charged with current and multiplexing control. The study reiterated the importance of safe charging infrastructure as the growth and development of EVs increases worldwide. The findings revealed that EVs required the option to shut off or lower the power to EVs in the event of a safety breach. In addition, the study demonstrated the potential of an intelligent charging infrastructure that can power numerous EVs through a single circuit to ensure multiplexing power, charge control and safety systems that avert electric shock. Similarly, De Castro *et al.,* [45]proposed and designed a safety system with safety-oriented strategies for control allocation in over-actuated EVs. Lv *et al.,* [37]proposed a novel control algorithm for braking energy regeneration systems in EVs. The objective was to ensure critical safety manoeuvres, vehicle stability, were carried out while driving EVs. The MATLAB/Simulink results showed that the conventionalapproachpermitsenhanced control of vehicle stability and braking performance in various emergency driving settings. In addition, the hardware-in-the-loop tests were conducted to validate the synthesized control algorithm and found to verify not only the simulation data but also the viability and efficiency of the established control algorithm. Similarly, the study by Xu *et al.,* [36]investigated the effect of the electrified control of regenerative braking used for deep energy recovery and maintaining safety in EVs. The findings showed that the proposed system helped to prevent the complex determination of the optimum slip ratio even during the process of obtaining the approximate anti-skid performance for braking. Furthermore, it was observed that the stability maintenance and performance improvement of the regenerative braking system requires maximum adhesion force and motor reference torque. More recently, Qiu *et al.,* [46]proposed an innovative strategy for the control of regenerative braking in EV systems for ensuring the vehicles adhere to strict safety guidelines for critical driving settings. The objective was to ensure the stability of EVs under different types of tire-road adhesion settings. The attributes of the electric powertrain, which is a new strategy for the control system for regenerative braking, was developed for anti-lock braking proceduresin EVs.

In the study by Campi *et al.,* [47], the authors aimed to investigate the safety compliance and related issues with the EMC and EMF for wireless charging of the batteries of EVs. Hence, the electromagnetic field in the WPT coils and chassis of the EV was examined by coding using FEM (finite element method). Similarly, a group of Xu *et al.,* [48]carried out an investigation on the safety and environmental impacts of electromagnetic fields associated with the wireless power transfer technology typically used for the charging of an EV system. The objective was to examine the effect of such systems on human safety during charging or the use of EVs using proprietary software for simulating 3D electromagnetic. The findings revealed that the highest current density, power density, and SAR values 20.058 mA/m^2, 1.22×10^{-5} W/m^2 and 4.37×10^{-7} W/kg, respectively, are below the safety limits of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) procedures. Hence, the electromagnetic settings of the EVs examined were found to be safe for human use. In a more recent study, Hu *et al.,* [25]also proposed a novel predictive control model and multi-objective control framework for enhancing the fuel economy, emission cutbacks, and the inter-vehicle safety of EVs. The findings demonstrated the interplay between fuel economy, vehicle exhaust emissions, and inter-vehicle safety.The results showed that the suggestedcontroller effectively reducedthe fuel consumption by 10.49% along with the emissions of CO (48.02%), NOx (22.79%)and HC (55.38%)in EVs.

Pardo-Ferreira *et al.,* [26]investigated the impact of the low noise levels andwork-based road safetyof EVs. The study demonstrated that the noise levels of EVs could pose risks to the health and safety of users, although the risk level was described as medium. However, EVs are required to integrate sound minimizing technologies or non-acoustic solutions in the US and European Union (EU) zone.Wu *et al.,* [27]modelled the vehicular safety of EVs equipped withusing theBayesian Network (BN) modelling approach. The findings showed that the safety of EVs is also influenced by other factors such as their transport from location to location. In the study, the transport of EVs using RoPax ships to elucidate the impact of maritime transportation conditions (such as initial exothermic temperature, self-heating rate, pressure rise rate) owing to the chemical reactions, complex mechanisms, and hazard characteristics associated with this form of transportation. The study revealed the crucial failure patterns and potential explosionsthat could occur during marine transportation of EVs could be minimized or averted in their entirety by charging the EVs.

4. CONCLUSIONS

The study examined the publication trends, research landscape, and scientific developments on electric vehicles safety (EVS) research from 2006 to 2021. The published documents data on EVS research was obtained from the Elsevier Scopus database based on the search query developed from the title keywords “electricvehicles” and “safety”. The search recovereda total of 220 published documents in the form of conference papers, articles, reviews, book chapters, among others. The research landscape analysis showed that Zhenpo Wang (Beijing Institute of Technology) and the duo Ming H. Lu and Ming U. Jen (Industrial Technology Research Institute of Taiwan) are the most prolific authors and affiliations on the topic. The largest funder and countries actively researching topics on

EVS research are the National Natural Science Foundation (NSFC) andthe Peoples' Republic of China(PRC), respectively. The findings also showed that significant financial support and non-monetary resources had been devoted to EVs and EVS research, thereby resulting in numerous scientific developments and published documents on the topic during the time span examined in the study. The most notable developments have been on improvementsin the efficiency and safety of Li-ion batteries, particularly with regards to operational/use problems such as thermal runaway, pressure, shocks, explosions, and other risks associated with battery damage. Overall, the findings showed that the research impact and scientific developments on EVS research are projected to grow in the coming years, particularly against the backdrop of growing calls to reduce fossil fuel dependence and GHG emissions from the transportation sector. Finally, this study offers wide-ranging information on the research landscape, scientific developments, and understandings that can be vital to scholars, industries, and policymakers in EVS research.

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