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Review

Analysis of Electric Vehicle Battery State Estimation Using Scopus and Web of Science Databases from 2000 to 2021: A Bibliometric Study

Radhika Swarnkar, R. Harikrishnan * and Mangal Singh

Symbiosis Institute of Technology (SIT), Symbiosis International Deemed University (SIDU), Pune 412115, India
* Correspondence: dr.rhareish@gmail.com

Abstract: This paper presents a bibliometric analysis of battery state estimation in electric vehicles. In this paper, a quick study is performed on the top global research contributors, funding agencies, and affiliate universities or institutes performing research on this topic while also finding the top keyword searches and top authors based on the most citations in the field of electric vehicles. Trend analysis is done by using the SCOPUS and Web of Science (WOS) databases (DB) from the period of 2000 to 2021. Battery state estimation plays a major role in the battery present state based on past experience. Battery available charge and health knowledge is a must for range estimation and helps us acknowledge if a battery is in useful condition or needs maintenance or replacement. A total of 136 documents in SCOPUS and 1311 documents in Web of Science were analyzed. Through this bibliometric analysis, we learn the top authors, country, publication journal, citation, funding agency, leading documents, research gap, and future trends in this research direction. The author Xiong Rui has the most publications, and he is working at the Beijing Institute of Technology, China. The most common institution is the Beijing Institute of Technology, and China is the most highly contributing country in this research. Most of the publications are conference types in SCOPUS DB and article types in WOS DB. The National Natural Science Foundation of China provides the most funding. The journal *Energies* has the most publications related to this field. The most cited works are by the authors M.A. Hannan and L.G. Lu in SCOPUS and WOS DB, respectively. A statistical analysis of the top ten countries' productivity results is also discussed.

Keywords: bibliometric analysis; battery management system; state of charge; state of health; lifetime prediction

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1. Introduction

Nations of the world are trying to reduce their carbon footprints by way of sustainable development. The automotive industry has advanced in its technologies and stepped toward electric vehicles. The journey of the electric vehicle (EV) started in 1835 with a non-rechargeable battery. As the population increases, the demand for automobiles for transportation also increases day by day. Electric buses [1] have advantages like reduced pollution and noise, but they also pose some challenges like charging demand modeling and their impact on the power grid. Lithium-ion batteries have high energy density and are used for uninterrupted power supply (UPS), smart phones, EVs, and electronic devices in airplanes and military services. The characteristics of lithium-ion batteries are non-linearity and unpredictability. The battery will explode if not handled with care; therefore, a state of charge (SOC) estimation and state of health (SOH) estimation is necessary. The SOC estimation is essential for a series-parallel combination of batteries to check for the imbalance of charge capacity in individual cells. This imbalance will shorten the battery life [2]. Accurate SOC estimation is important for enhancing driver's safety, re-routing, comfort, control, and protection from the full discharge of the battery. Proper predictive

maintenance is required. Forecasting of SOC by using ML algorithms like ARIMA, LSTM, and XGBoost are carried out in [3], where XGBoost and ARIMA show fewer errors as compared to LSTM. The major components in EVs are the battery, motor, and controller. A battery pack is comprised of electrochemical cells, and protection of each cell from overvoltage, overcurrent, and overcharge/discharge are difficult to manage. In order to enhance the battery performance, it is necessary to estimate battery health and predict aging conditions. EV users' driving and charging behaviors are diverse, and battery health assessment is costly and difficult for EV manufacturers to periodically analyze. By using statistical analysis of the stored data, it is easier to analyze aging indicators. Calendar aging and cycling have a high impact on lithium batteries when in use. Driving EVs at high SOC has the most significant impact on battery aging, and driving at a high cycling rate or fast charging leads to a high discharge current and even damage to the material composition of a lithium battery [4]. The lithium-ion battery changes its behavior in different operating conditions; therefore, nonlinear characteristic analysis is necessary in order to predict its state. It is necessary to account for different battery characteristics in different scenarios when conducting an analysis. By analyzing different cells at different temperatures and charging current rates, state health can be estimated. A partial charge voltage curve-based health indicator is used to predict the remaining useful life (RUL) of the battery [5]. In order to drive an EV, a high-capacity and high-power battery are deployed in the chassis of the vehicle. The arrangement of cells is in a series-parallel fashion, and each cell's temperature, overcurrent, overvoltage, protection, and durability monitoring are difficult to manage. EV battery cost is very high, and battery non-linear characteristics are unpredictable. Major challenges are battery lifetime prediction, the lack of a direct measurement of battery SOC, SOH, and end of life (EOL), protection issues, and safety. A battery management system (BMS) plays a major role in lithium-ion batteries for protection, diagnosis, sensing, interface communication, and performance management. BMS is an electronic controller which communicates between hardware like sensors and software algorithms. BMS is required for cell balancing, charge control, state estimations, and prediction of RUL. Lithium-ion batteries are mostly preferred over NiMH and Ni-cadmium batteries due to their low weight, high energy density, and low self-discharging rate [6]. Early detection of a fault or inadequate performance of the battery will save lives from severe danger. For applications in which available energy plays a major role in EVs, capacity is taken for SOH characterization. For applications wherein power plays a major role in EV, internal resistance is used for SOH parametric characterization.

Bibliometric analysis is important for identifying leading authors, co-authors, funding agencies, countries of origin, the articles with the most citations, and the top keyword searches in the area of BMS state estimation. The objective of this bibliometric study is based on research questions such as:

Q1. What is the global trend of scientific publications on BMS state estimation of EVs?

Q2. Who are the prominent authors and what are the countries contributing to this area of research?

Q3. How many papers are published in this research field?

Q4. How many citations were gathered by the top author and which journal has the most citations?

Q5. Which information is covered or uncovered in this area of research?

Q6. What are the future directions of this research work?

In order to address the above problem and begin research on an EV battery state estimation, the bibliometric analysis is carried out as a necessary step. Researchers in the particular specialization will be able to gain basic knowledge about that particular topic, key authors, contributing country, funding agency, affiliation, work direction, research gap, and future research trends. Research related to EV batteries is a trending topic. But most of the research problems related to EVs and batteries are unexplored, such as why EVs catch fire suddenly, the issue of the design and cooling of the battery, manufacturing, and issues related to the disposal and recycling of the battery need to be addressed. A

bibliometric study gives a brief idea of how to search keywords, and how to find topic-specific authors, countries, funding agencies, documents, and affiliations. The paper is organized as follows. Section 2 enlists the bibliometric articles in this field. Section 3 describes how this bibliometric analysis has been conducted with the road map. Section 4 elaborates the analysis of the bibliometric study. Section 5 discusses research trends and research gaps in this area of research. Section 6 concludes the paper with future directions for implementation.

2. Related Work

Bibliometric analysis is a quantitative analysis conducted on the basis of a database provided by books, articles, and publishing bodies like SCOPUS, Web of Science (WOS), ABCD, PubMed, EBSCO, and CrossRef. The bibliometric study is conducted on the basis of the scientific method that uses mathematical equations and statistical tools to evaluate the output. The bibliometric study helps researchers, scholars, and beginners in their respective research domains to initiate and start their work and also helps to narrow down the broad area of the research statement. For this bibliometric study, the SCOPUS and WOS databases were used. Similar, bibliometric analysis with a different domain and database done in reference [7]. The data collection of all the scientific publications from all of history was done on 23 September 2021. The bibliometric analysis was applied to various fields such as visualizing features, status, development, latest trends, and research gaps. This helps scholars, manufacturers, professors, and researchers who are not experts in the field to get a summary of knowledge in a given area. This analysis also helps manufacturers and experts to create a better model of BMS for better state prognosis in real-time. Software tools like VOSviewer, CiteSpace, and HitsCite are used for finding the correlation between author and keywords in the form of a bibliometric network.

A scientific and comprehensive study of bibliographic data has increased the number of bibliometric reviews in different fields. Different techniques were applied to extract appropriate data and visualization. Table 1 lists the related bibliometric method and EV bibliometric database for the study. The bibliometric study allows the reader to identify the main research domain variable within a short span of time. Reference [8] presents a business model in terms of services, charging technology, energy management, production plant, and the leasing of batteries/electric cars. The government is trying to boost the EV sector by giving subsidies, but the development progress is still slow in this sector as there are a lot of unexplored research areas in this sector. Reference [9] presents a bibliometric analysis in thermal management of batteries in which the author discussed different methods of cooling and heat transfer in different batteries and cars. Reference [10] discusses the energy management of a hybrid electric vehicle (HEV) and its environmental impact. Reference [11] discusses the development, changes, and challenges in EVs over a decade. Reference [12] discusses the development and implementation of EVs so far and the areas that need to be explored. Reference [13] presents a life-cycle cost analysis based on different models. Policies, subsidies, and business plans are described in this paper. Reference [14] discusses the latest trends and work on blockchain technology through bibliometric analysis. Bitcoin, cryptocurrency, security, and smart contract are the hot research topics in blockchain technology. By understanding this topic thoroughly, many of the blockchain issues will be solved. In [15], energy management by a rule-based approach and by an optimization-based approach is discussed. Reference [16] presents a simulation model for lithium-ion battery lifetime prediction under real-time operating conditions. A semi-empirical accelerated aging model is used to parameterize the model. Fusion-based open-circuit voltage (OCV) and incremental capacity analysis (ICA) is used as a robust method for accurately estimating SOH and is discussed in [17]. Reference [18] discusses about the estimation of hybrid and battery electric vehicle management, its control and battery unit management. Reference [19] discusses calendar and cyclic aging tests for the lithium-ion 18,650 battery. Factors that influence calendar aging are temperature and voltage, whereas factors that influence cyclic aging are cycle depth and average SOC.

Table 1. List of study related to the Bibliometric method and EV.

References	Area of Bibliometric Study	Journal Published	Tools Used
[8]	Business model of electric cars	Journal of Cleaner Production	R-Software, Biblio Shiny
[9]	Thermal management of batteries	Journal of Energy Storage	VOSviewer
[10]	Energy management in HEVs	International Conference-Electronics, Computers and Artificial Intelligence (ECAI)	VOSviewer
[11]	Evolution in EVs over a decade	ARPN Journal of Engineering and Applied Sciences	HitsCite
[12]	Identify development in EVs	European Journal of Molecular & Clinical Medicine	VOSviewer
[13]	Life-cycle cost analysis of EV	Sustainability	VOSviewer
[14]	Blockchain technology	Future Generation Computer Systems	Cite Space, VOSviewer
[15]	Energy management in HEVs	Renewable and Sustainable Energy Reviews	Excel

Given above is the table of bibliometric studies of EV development, policies, subsidy plans, and research areas. Some papers on different topics of bibliometric study are referred to so as to gain knowledge of which visualization tools are used in that paper, how they have done the analysis and the purpose of the study.

The review paper is basically a deep analysis of the literature related to the topic and requires a short summary of all the past work done, an analysis of information and methodology, the advantages/disadvantages, limitations, and future scope. Some review papers are discussed in Table 2. In contrast, a bibliometric paper is a short analysis of research trends, top documents, top authors and co-authors, top citations, publishing bodies, the top titles of the papers, top keywords, top affiliations, countries working on that area, and year-by-year analysis.

Table 2. List of the study related to review documents.

Review Document	Discussion	Advantage	Disadvantage
[18]	• Review of different hybrid and electric vehicle estimation strategies are discussed. • Estimation related to battery management, vehicle management, and vehicle controls are discussed.	Cover many estimation strategies and parameters which controls and manages vehicle dynamics.	Short discussion on the existing estimation strategies related to vehicle and battery management. Detailed discussion of advantage and disadvantage of different methods is missing.
[20]	• Different challenges in BMS and methods to overcome that challenge is discussed. • Detailed discussion of working of BMS in EV.	Cover different challenges and techniques to identify parameters in BMS are discussed.	BMS challenges for EV are discussed but comparison of techniques to identify parameter is not discussed.
[21]	• Real-time SOH estimation methods for hybrid vehicles are discussed. • Experiment-based, model-based, and ML-based techniques are discussed.	Discuss methods for real-time hybrid EV for accurate timely maintenance. Battery internal resistance is the key indicator for battery degradation.	Discuss few techniques of model-based and ML-based approach for hybrid EV application. Considering battery internal resistance as the key indicator for battery aging whereas other indicators like capacity, humidity, temperature, environment, and driving pattern which also play a major role in battery aging are not considered in this paper.

Table 2. *Cont.*

Review Document	Discussion	Advantage	Disadvantage
[22]	Different BMS state estimation techniques and their research trends in past 3 years are discussed.	Research trends in past 3 years in the field of SOC, SOH, SOT, and SOF are discussed in detailed manner. Knowledge about recent research trends will help in further exploration of new techniques to estimate state accurately.	Comparison between different methods of state estimation along with accuracy results and dataset of different battery chemistry under different conditions effect in state estimation are missing in this paper.
[23]	Different estimation methods for SOC, SOH, SOP, capacity estimation, RUL and battery impedance estimation for electric and hybrid vehicles are discussed.	Cover different battery state estimation methods in a detailed and flowchart manner.	Advantages and disadvantages of different state-estimation methods on different chemistry and environment conditions of battery are not discussed in this paper.
[24]	Detailed discussion of SOC methods and SOC methods for battery.	Different approaches to estimate SOC are discussed.	Comparison between methods of SOC estimation is lacking in this paper.
[25]	Review of SOC, voltage estimation, capacity estimation and RUL are discussed.	Parameters and conditions for state-estimation methods used in different literatures are discussed.	Comparison between different estimation methods are lacking in this paper.

There are various highly cited bibliometric papers in the year 2021–2022 in different domains such as eye health/vision impairment [26], the effect of knowledge management in industrial 4.0 [27], global geoparks analysis [28], transfer pricing [29], and security aspects related to the smart grid [30] policy analysis using data science [31].

Bibliometric analysis is an overview or shallow discussion of a paper, whereas a review paper is an in-depth discussion. How to conduct a bibliometric analysis is described in detail in [32]. In [26], the author has provided a detailed analysis report of vision impairment, its causes, and its effect on health. Women are mostly suffering from eye health issues as compared to men. This gender imbalance is due to demographic and socially related factors. Women are less cared about with regard to their health, save money for their families, and do not spend money on their own health-related problems. Transfer pricing (TP) [29] refers to financial transactions within or in between the enterprise members. TP plays a significant role in an organization as it directly reflects organization pricing, revenue, and profitability. TP analysis helps in tax saving and avoiding unnecessary penalties. There are various types of cyber threats in a smart grid, and the way to mitigate cyber threats, as well as future directions in this area, are discussed in [30].

3. Methodology

The bibliometric analysis is done in five steps: the purpose of study design, data collection, and analysis of data, data visualization through tools, and inference from data which is shown in Figure 1. Bibliometric analysis is a scientific method conducted through mathematical calculations and statistical analysis. The main objective of this research is to find which author, country, journal, keyword, subject area, year, language, and institution is dominant in the state estimation of the EV battery.

The first phase started with research-based questions. Appropriate keyword selection for analysis is also a topic of concern. The gathering of keywords is done from highly cited publications along with essential keywords according to the author [8]. Relevant databases from SCOPUS and WOS were explored for the review articles related to state estimation of electric vehicle batteries.

In the second phase, data collection is done with the appropriate keyword and with filtering elements like publication, year, subject, keyword, author, citation, and institution. Applying Boolean logic operations in keyword searches also gives different results for documents. Using an inverted comma in each keyword will not allow two or more words in a block to separate. Using a single colon in a keyword means a suitable suffix along with

a keyword will search and give results. We fixed year constraints as selection criteria for database extraction, and we limited the years of investigation to be from 2000 to 2021.

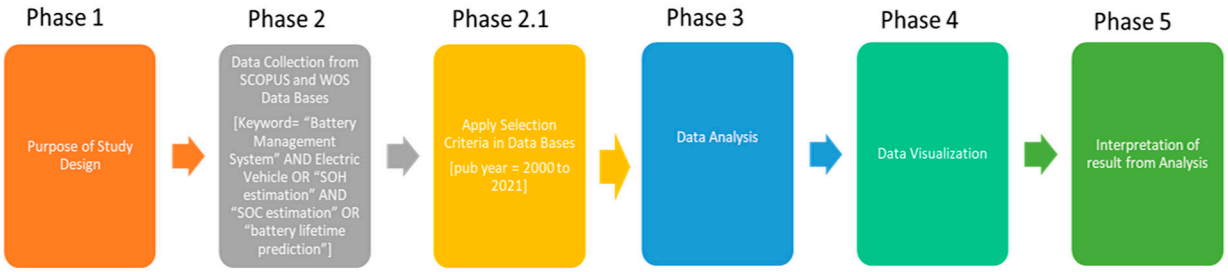

Figure 1. Methodology step by step phase process.

In the third phase, data analysis is done. After downloading the CSV file, normalization of the data is done if there is missing/redundant/oversampled data. We mapped the data network and moved to the next step.

In the fourth step, data visualization is done. There are many visualizations open-source software tools available like VOSviewer, CiteSpace, Hitscite, Gephi, Wordcloud, Excel, Orange, R software, MiniTab, and TABLU. In this paper, the authors used Wordcloud, Excel, and VOSviewer as visualization tools.

In the final phase, inferences were drawn from the available data visualization. This result helps in concluding the research-based questions answers. Inference from the bibliometric study also helps find literature gaps, future trends, and the amount of work that has been done in a particular research area. The bibliometric study is a history of scientific publications on a particular topic within a short span of time.

3.1. Significant Keywords

The searched keywords are "battery management system" AND "electric vehicle" OR "SOH estimation" AND "SOC estimation" OR "battery lifetime prediction". Primary and secondary queried keywords are shown in Table 3. By using only primary keywords, there are 5129 documents in SCOPUS and 1339 documents in WOS. Then adding specialized keywords specific to a particular topic that is using primary as well as secondary keywords by "ORing" the result will bring 828 documents in SCOPUS and 1434 documents in WOS. By using the above query string keywords with Boolean logic along with the year constraint (2000 to 2021), there are 136 documents in SCOPUS and 1311 documents in WOS. On the left-hand side of SCOPUS and WOS library, there are options to exclude or limit country, publication type, language, affiliation, and many more parameters. The correct incorporation of keywords helps to reach the target research areas in terms of the number of publications (NoP). WOS has more documents searched as compared to SCOPUS.

Table 3. Keywords used for querying SCOPUS DB and WOS DB (Source: SCOPUS DB and WOS DB accessed on 7 March 2022).

Keyword Type	Keyword Combination
Primary keywords (SCOPUS DB and WOS DB)	"battery management system" AND "electric vehicle"
Secondary keywords (SCOPUS DB and WOS DB)	"SOH estimation" AND "SOC estimation" OR "battery lifetime prediction"

The search of appropriate keywords and the time duration over which this keyword is searched also plays an important role in finding relevant data. Tips to search results in different ways are discussed in Table 4, which helps researchers to fine tune and narrow down their research topic.

Table 4. Tips to search relevant document result in different ways of keyword search.

Operator	Symbol	Description with Example
Truncation operator	$	Search zero or more characters in between letters e.g.- colo$r = color, colour
Truncation operator	* *	Search zero or more characters in suffix/prefix e.g.- *carbon* = hydrocarbon, carbon, carbonate
Truncation operator	?	Search one character only in between letters e.g.- en?oblast = endoblast, entoblast
Boolean operator	AND	All search terms must occur to be retrieved e.g.- stem cell AND lymphoma
Boolean operator	OR	Any one of the search terms must occur to be retrieved e.g.- stem cell OR lymphoma
Boolean operator	NOT	Excludes records that contain a given search term e.g.- pigment NOT greenIt retrieves pigment terms documents which does not include green
Proximity operator	" "	In order to search for an exact phrase, enter the term in quotation marks. Use of quotation mark disables the lemmatization of terms. e.g.- "electric vehicle" It shows documents related to electric vehicle term only

3.2. Preliminary Analysis

WOS has more publications than the SCOPUS DB, which is clearly seen in Figure 2. There is a drastic increase in NOP from 2014 to 2021 in both databases. Awareness programs, promotion through social media, subsidy missions, and research trends in the EV sector increased starting in 2018.

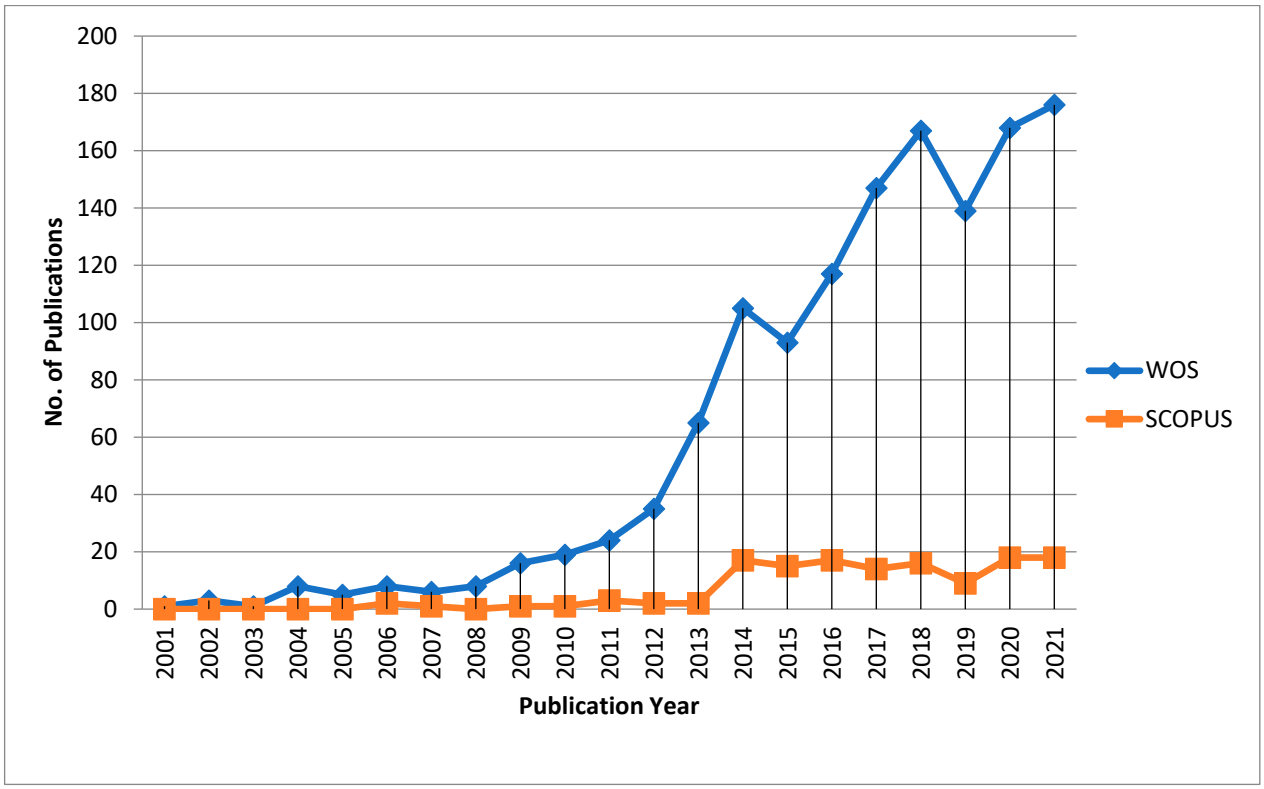

Figure 2. Total number of publications between 2000 to 2021 in SCOPUS and WOS databases.

In Figure 3, the top ten most influential authors of EV BMS in both SCOPUS DB and WOS DB are listed. Rui Xiong is the author with the most contributions with total 52 publications, followed by Minggao Ouyang with total 50 publications in WOS DB. Rui Xiong is the most contributing author in SCOPUS DB with 8 publications followed by Hongwen He with 5 publications.

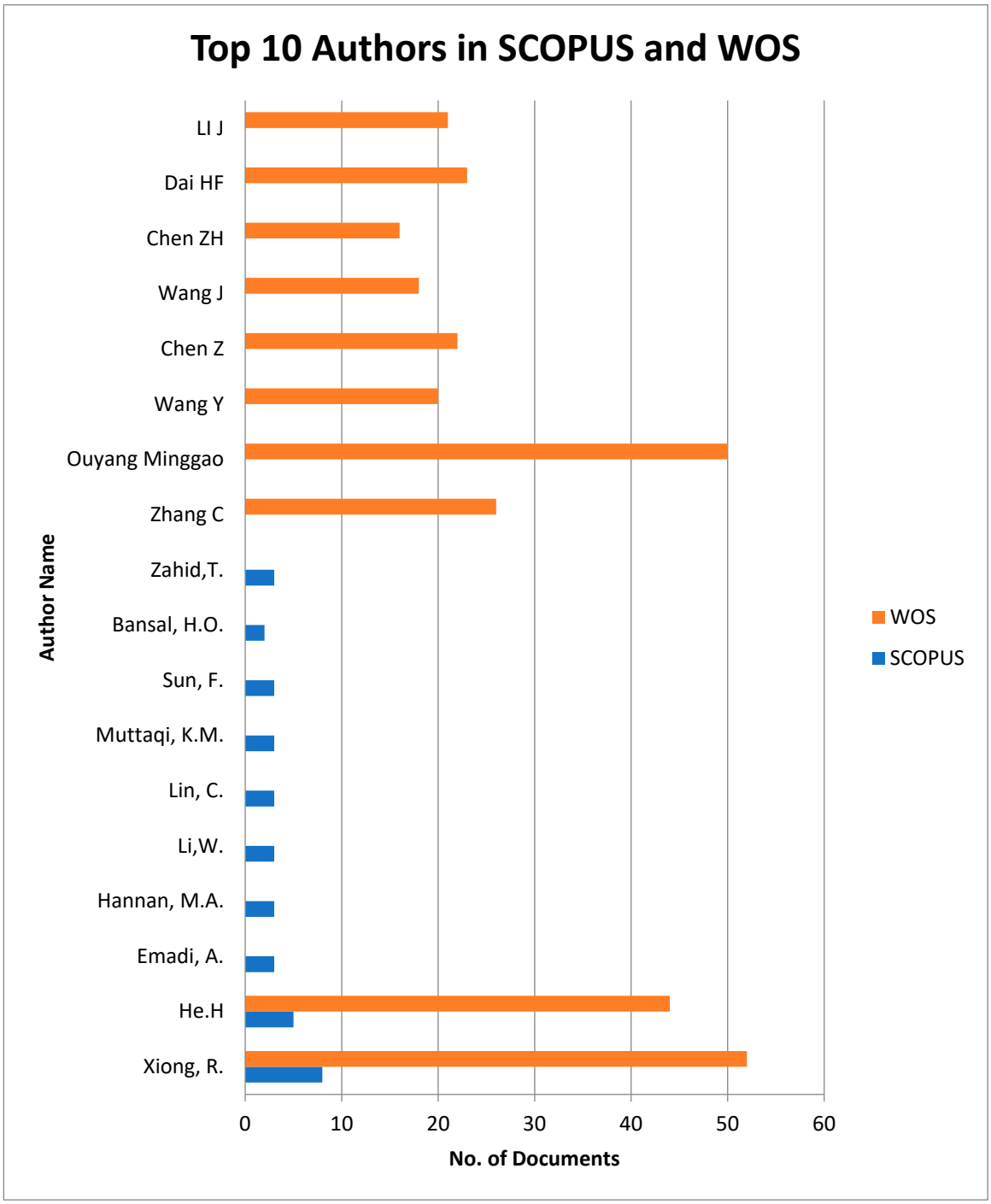

Figure 3. Top ten authors of SCOPUS and WOS DB along with NOPs.

Figure 4 shows the top ten affiliations in SCOPUS and WOS DB. The Beijing Institute of Technology leads with 14 publications followed by the Chinese Academy of Sciences with 11 publications in the top ten affiliated publishing institutes in the SCOPUS DB lists. The

Beijing Institute of Technology leads with 105 publications followed by Tsinghua University with 89 publications in the top ten affiliated publishing institutes in the WOS DB lists.

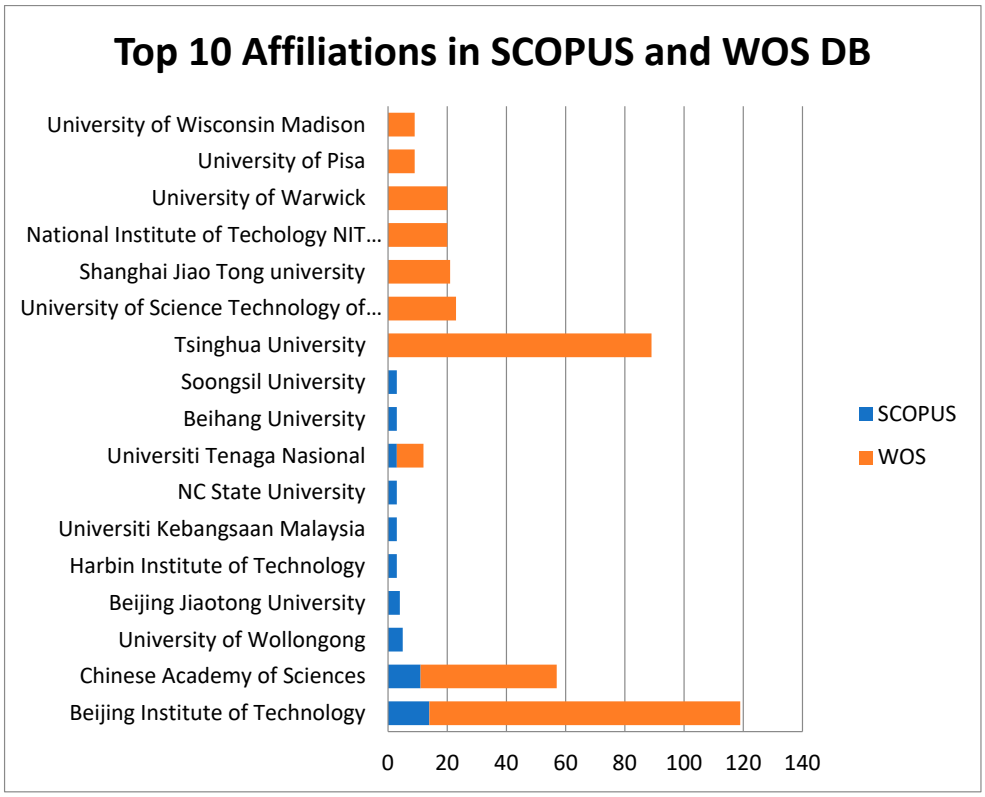

Figure 4. Top ten affiliations in BMS EV in SCOPUS and WOS DB.

The categories of documents for publication are shown in Figures 5 and 6 for SCOPUS DB and WOS DB respectively. Conference paper publications are most prevalent with 74 documents, followed by article-type documents with 58 documents, and then review-type papers with 4 documents in SCOPUS DB. Article-type publications are most prevalent in WOS DB with 763 documents, followed by meeting-type papers with 616 documents. The other categories of WOS DB publications are review, early access, and books.

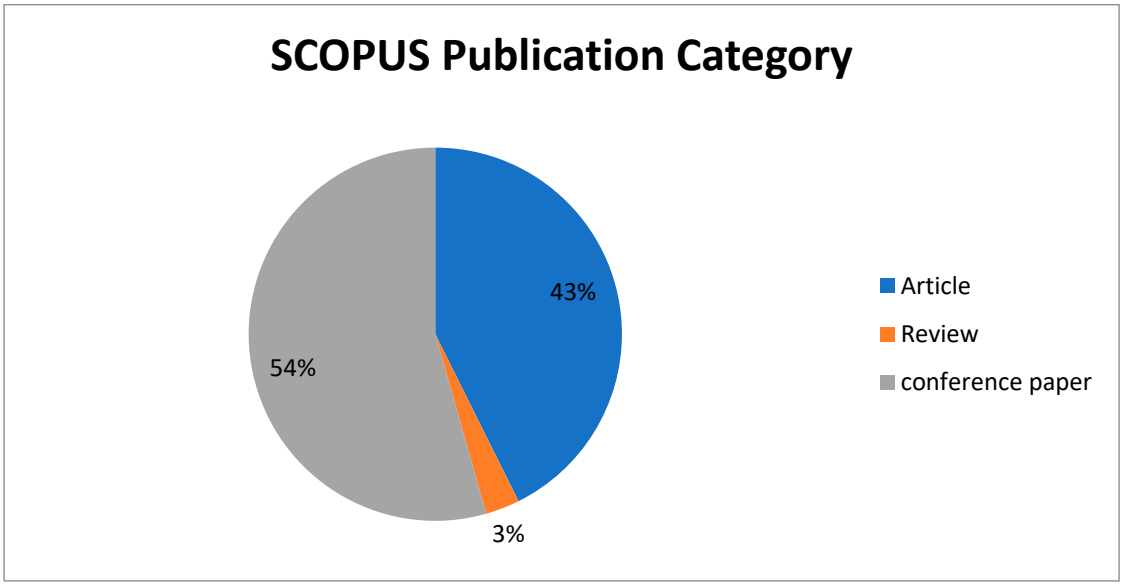

Figure 5. SCOPUS DB publication category in the field of BMS EV.

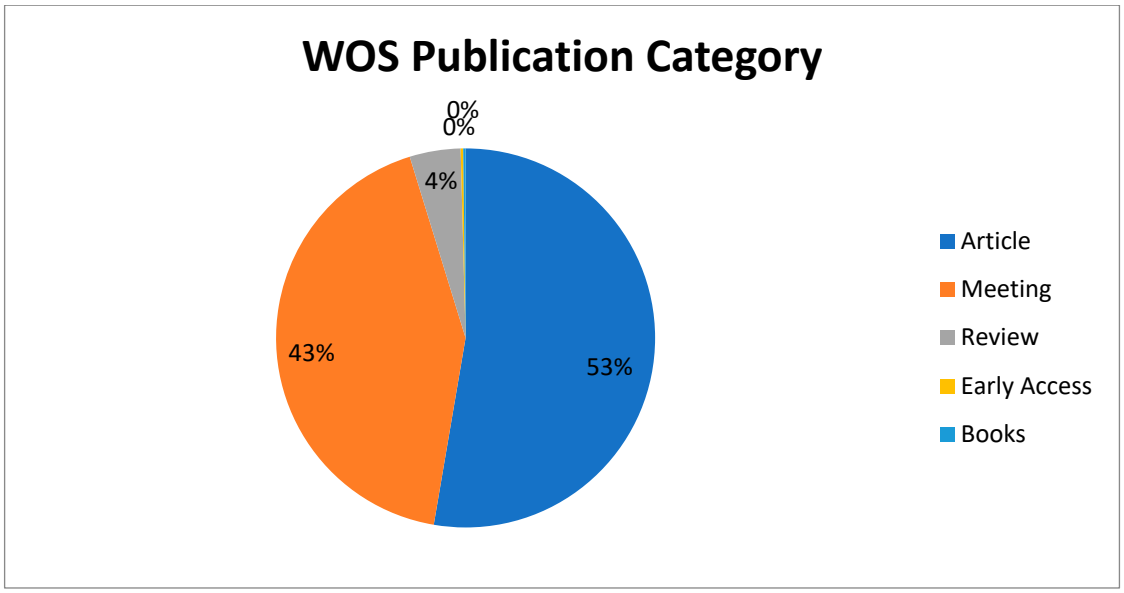

Figure 6. WOS DB publication category in the field of BMS EV.

Numbers related to publications' countries of origin are shown in Figure 7. China has the most publications with 72 documents, followed by India with 16 documents in SCOPUS DB. China has the most publications with 827 documents followed by the USA with 215 documents in WOS DB. China is the top contributor to the EV battery research field because of the following reasons.

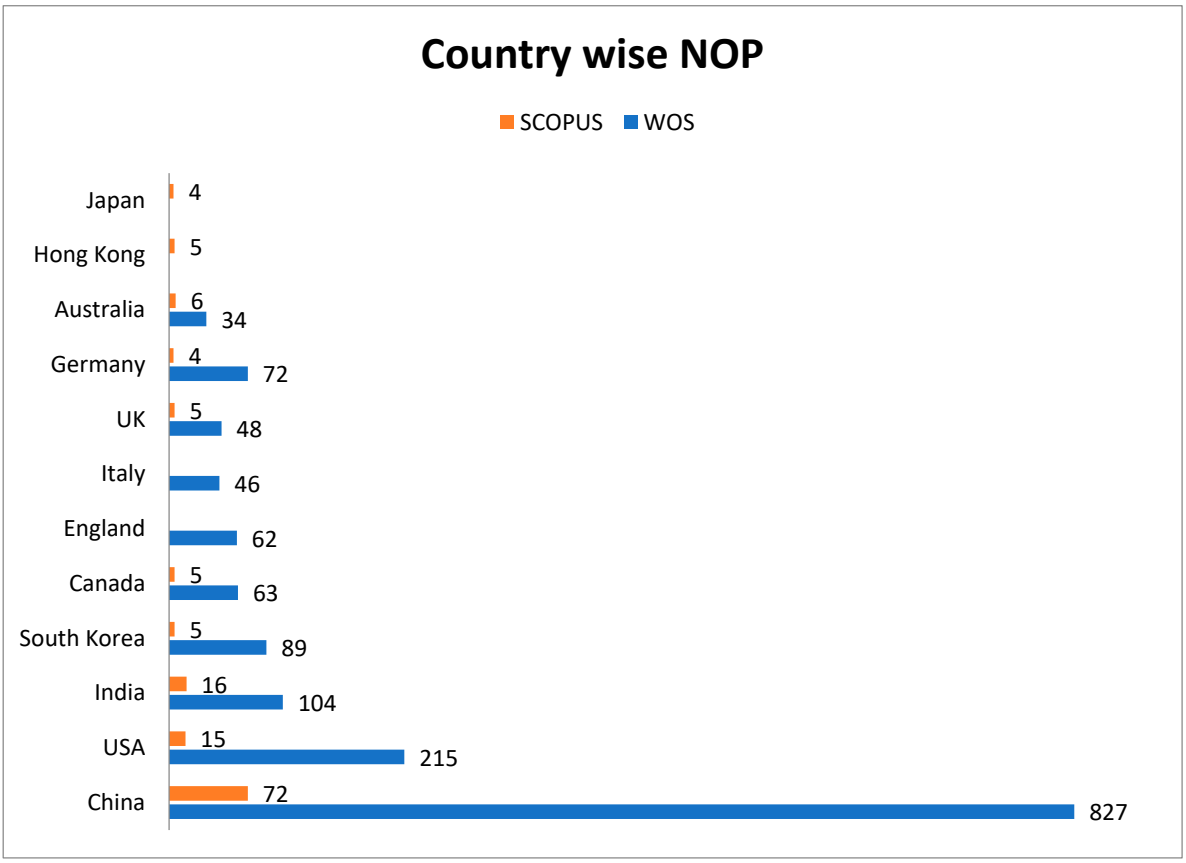

Figure 7. Based on country-wise NOP in SCOPUS and WOS DB.

As per the SCOPUS database, Table 5 shows the top ten countries with maximum publication and the top ten highly cited papers' countries. The statistical t-test is conducted for finding the difference between top ten countries' productivity. The null hypothesis is there is no difference between the number of publications of the top ten most highly cited papers' countries and the maximum number of publications from top ten countries. In the alternative hypothesis, there is a difference between the number of publications of top ten highly cited papers' countries and the maximum number of publications from top ten countries.

Table 5. Comparison of top ten countries in all and highly cited paper countries.

Countries	Max Publication Countrywise	Highly Cited Papers Countries	Highly Cited Publication Countrywise
China	72	Malaysia	2
India	16	China	28
United States	15	Canada	3
Australia	6	United States	1
Canada	5	Singapore	1
South Korea	5	India	4
United Kingdom	5	Australia	4
Germany	4	Iran	1
Japan	4	Turkey	1
France	3	Norway	1

One sample *t*-test is conducted, and Equation (1) shows the formula for the *t* ratio:

$$t = \frac{\overline{X} - \mu}{\frac{S}{\sqrt{n}}}, \quad (1)$$

where $\overline{X}$ is the calculated mean, μ is the hypothetical mean,

S is the standard deviation, and
n is the sample size.

JASP is an open-source software and can be downloaded freely. By using JASP software, statistical analysis was performed for this paper. Results are discussed in Tables 6 and 7. The *p*-value is more than 0.05 for both the sample publications, which means the null hypothesis is accepted and the alternative hypothesis is rejected. There is no difference between the number of publications of top ten highly cited papers countries and the maximum number of publications from top ten countries.

Table 6. One-sample *t*-test of top ten countries in all and highly cited paper countries.

One Sample *t*-Test			
	t	**df**	***p***
Max Publication Countrywise	2.026	9	0.073
Highly Cited Publication Countrywise	1.749	9	0.114

The top ten funding agencies of BMS state estimation in EV from SCOPUS DB and WOS DB is shown in Figures 8 and 9 respectively. The most documents are funded by the National Natural Science Foundation of China with 19 and 195 publications in SCOPUS DB and WOS DB, respectively. As per Figures 8 and 9, most of the funding comes from NSFC China. Figure 4 shows that most of the research articles are from the Beijing Institute of Technology. China has also a high lithium reserve.

Table 7. Descriptive statistics of top ten countries in all and highly cited paper countries.

Descriptive Statistics				
	Max Publication Countrywise	**Highly Cited Publication Countrywise**	**Countries**	**Highly Cited Papers Countries**
Valid	10	10	10	10
Mode	5.000	1.000		
Median	5.000	1.500		
Mean	13.500	4.600		
Std. Deviation	21.067	8.316		
Skewness	2.898	3.033		
Std. Error of Skewness	0.687	0.687		
Minimum	3.000	1.000		
Maximum	72.000	28.000		
25th percentile	4.250	1.000		
50th percentile	5.000	1.500		
75th percentile	12.750	3.750		

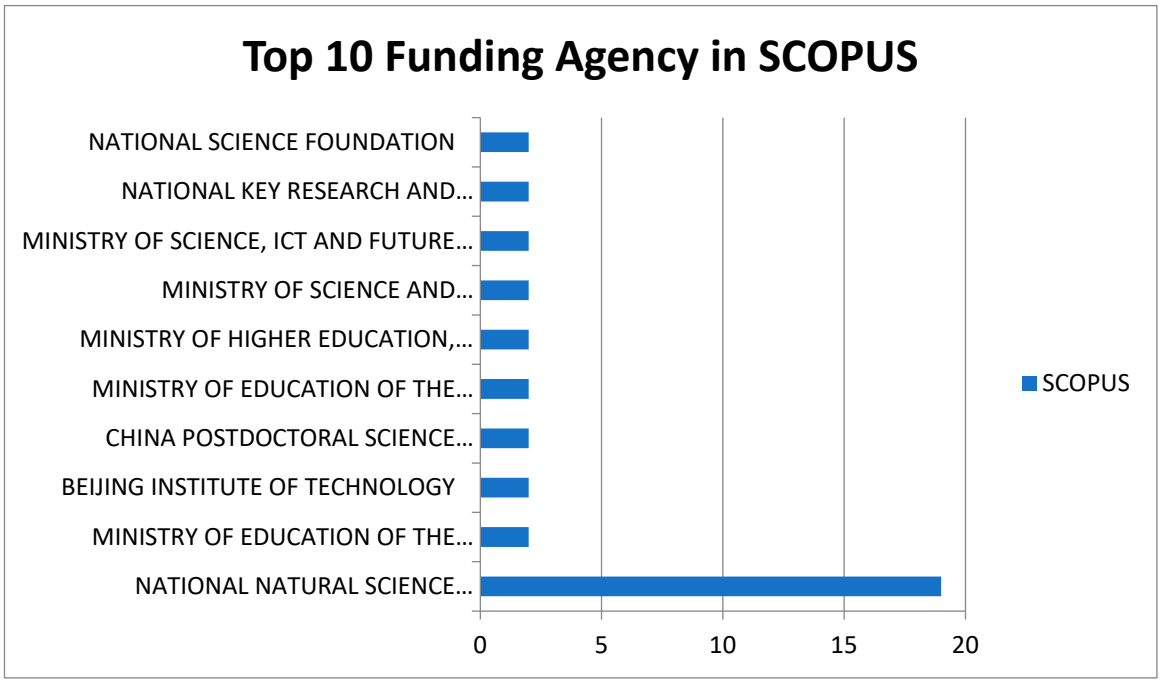

Figure 8. Top ten funding agencies in BMS EV for SCOPUS DB.

Figure 10 shows the number of publications in SCOPUS DB and WOS DB as per subject area. "Engineering" has the highest number of publications in both databases. A total of 1133 documents related to engineering were published in WOS DB followed by 986 "energy fuel" documents. A total of 108 documents were related to "engineering" in SCOPUS DB followed by "energy" with 52 documents.

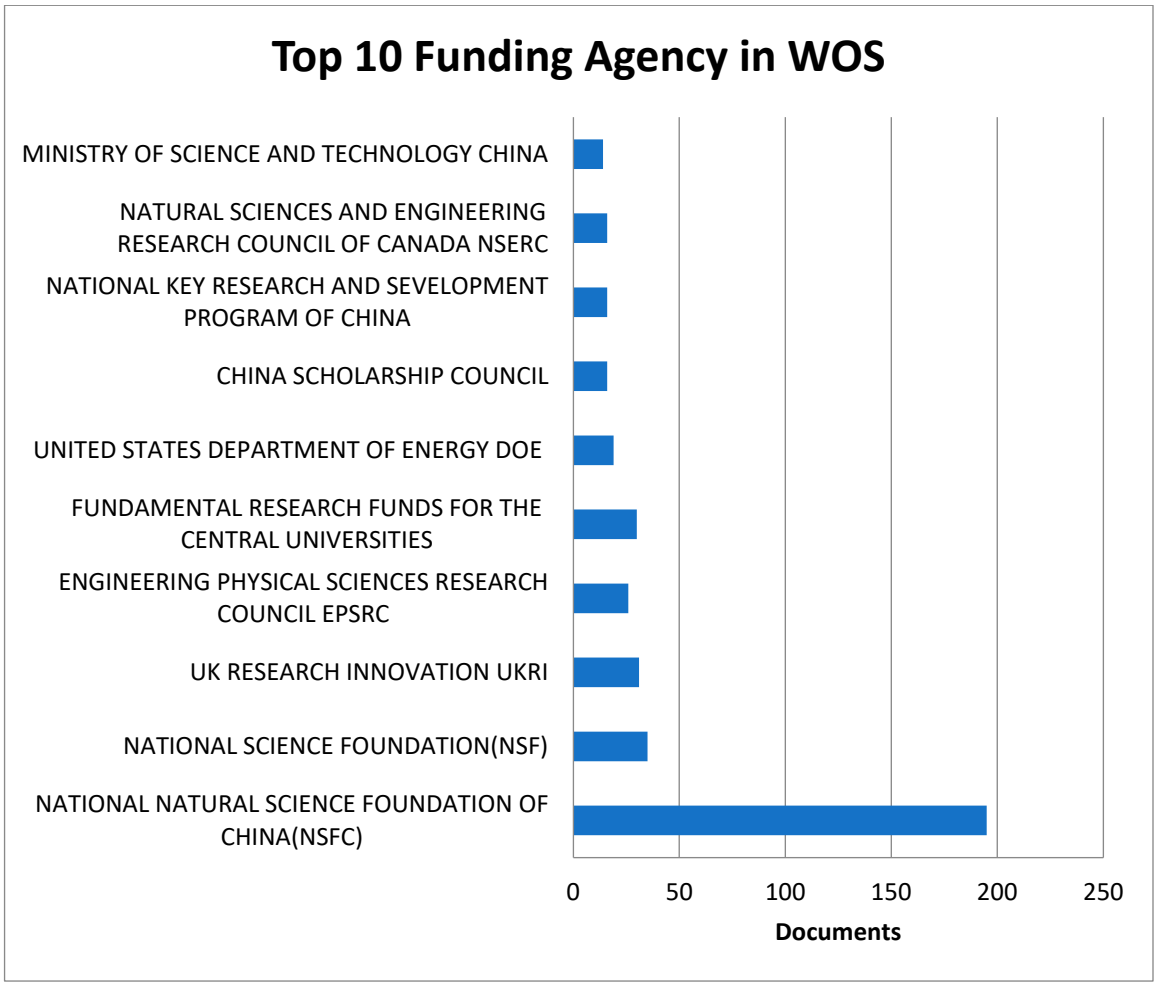

Figure 9. Top ten funding agencies in BMS EV for WOS DB.

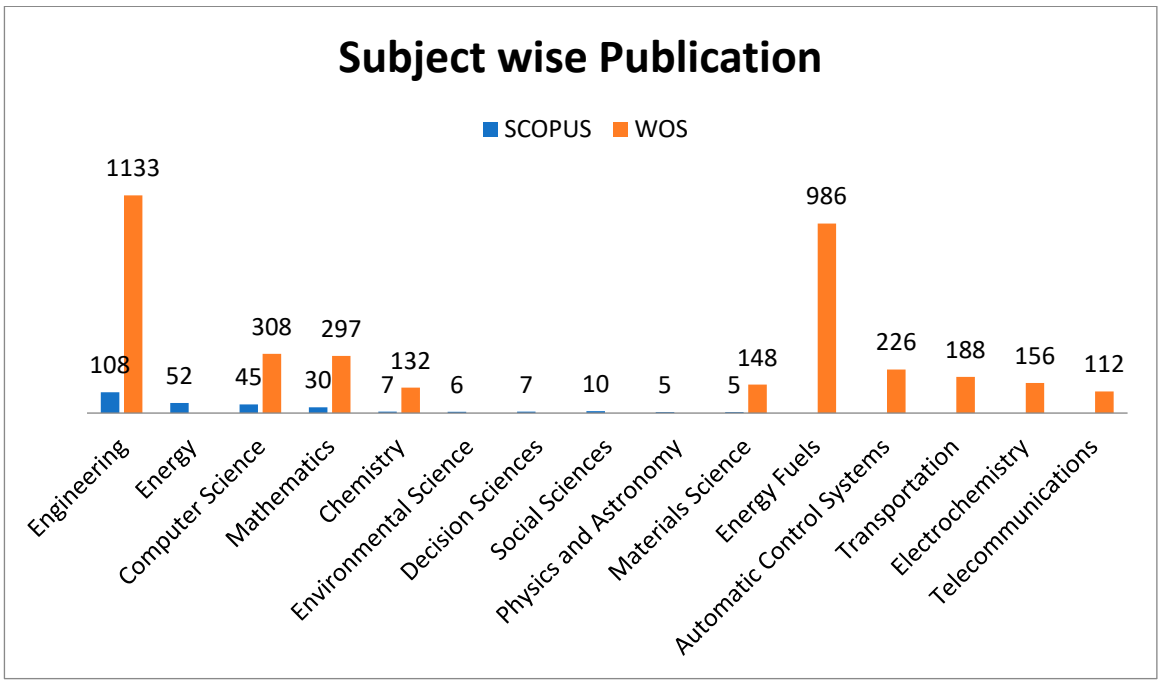

Figure 10. Subject-wise number of publications in SCOPUS DB and WOS DB.

4. Bibliometric Analysis

The citation shows which paper is referred to most of the time. The h-index is an indicator through which the evaluation of productive and influential authors is known. The h-index is calculated when the number of paper publications of an author is cited as greater than or equal to the number of papers published by the author. Tables 8 and 9 list the top 15 most cited papers in SCOPUS DB and WOS DB, respectively, along with publication year, title, author name, journal publication, and total citations gathered. M.A. Hannan had two SCOPUS documents published, one of which was a review paper on lithium-ion battery SOC estimation and management; this gathered 776 citations. L.G. Lu has one review paper on key issues of lithium-ion batteries in BMS, which gathered 2576 citations in WOS DB.

Table 8. Top 15 most cited papers in SCOPUS databases for BMS EV state estimation.

Sr. No.	Publication Year	Document Title	Author Name	Journal Name	Total Citation (<2021)
1.	2017	A review of lithium-ion battery state of charge-estimation and management system in electric vehicle applications: Challenges and recommendations	Hannan, M.A., et al.	Renewable and Sustainable Energy Reviews	776
2.	2011	Evaluation of lithium-ion battery equivalent circuit models for state of charge estimation by an experimental approach	He, H., et al.	Energies	616
3.	2014	State of charge estimation of lithium-ion batteries using the open circuit voltage at various ambient temperature	Xing, Y., et al.	Applied Energy	444
4.	2018	Long short-term memory networks for accurate state-of-charge estimation of Li-ion batteries	Chemali, E., et al.	IEEE Transactions on Industrial Electronics	220
5.	2018	Investigatingthe error sources of the online state-of-charge estimation methods for lithium-ion batteries in electric vehicles	Zheng, Y., et al.	Journal of Power Sources	193
6.	2014	State-of-charge estimation for battery management- system using optimized support-vector-machine for regression	Hu, J.N., et al.	Journal of Power Sources	133
7.	2015	Electric vehicle state of charge estimation: Nonlinear correlation and fuzzy support vector machine	Sheng, H., et al.	Journal of Power Sources	121
8.	2013	Battery state of the charge estimation using Kalman filtering	Mastali, M., et al.	Journal of Power Sources	118
9.	2018	Condition monitoring in advanced battery management systems: Moving horizon estimation using a reduced electrochemical model	Hu, X., et al.	IEEE/ASME Transactions on Mechatronics	106
10.	2016	Real-time estimation of battery state-of-charge with unscented Kalman-filter and RTOS µCOS-II platform	He, H., et al.	Applied Energy	81
11.	2016	An adaptive-sliding mode observer for lithium-ion battery state-of-charge and state-of-health estimation in electric-vehicles	Du, J., et al.	Control Engineering Practice	70
12.	2020	State-of-charge estimation of lithium-ion batteries using LSTM and UKF	Yang, F., et al.	Energy	59
13.	2012	Estimation of state of charge of lithium-ion batteries used in HEV using robust extended Kalman filtering	Zhang, C., et al.	Energies	57

Table 8. *Cont.*

Sr. No.	Publication Year	Document Title	Author Name	Journal Name	Total Citation (<2021)
14.	2006	Online SOC estimation of high-power lithium-ion batteries used on HEVs	Dai, H., et al.	2006 IEEE International Conference on Vehicular Electronics and Safety, ICVES	56
15.	2014	An online state of charge estimation method with reduced prior battery testing information	Xu, J., et al.	International Journal of Electrical Power and Energy Systems	52

Table 9. Top 15 cited papers in WOS databases for BMS EV state estimation.

S. No.	Publication Year	Documents Title	Author Name	Journal Name	Total Citation (<2021)
1.	2013	A review on the key issues for lithium-ion battery management in electric vehicles	Lu, L.G., et al.	Journal of Power-Sources	2576
2.	2004	Extended Kalman filtering for battery management systems of LiPB-based HEV battery packs—Part 3. State and parameter estimation	Plett, G.L.	Journal of Power-Sources	1159
3.	2004	Extended Kalman-filtering for battery management systems of LiPB-based HEV battery packs—Part 2. Modeling and identification	Plett, G.L.	Journal of Power-Sources	959
4.	2004	Extended Kalman -filtering for battery management systems of LiPB-based HEV battery packs—Part 1. Background	Plett, G.L.	Journal of Power-Sources	747
5.	2017	A review of lithium-ion battery state-of-charge estimation and management system in electric-vehicle applications: Challenges and recommendations	Hannan, M.A., et al.	Renewable & Sustainable-Energy Reviews	654
6.	2014	Critical review of the methods for monitoring of lithium-ion batteries in electric and hybrid vehicles	Waag, W., et al.	Journal of Power-Sources	578
7.	2013	Battery management system An overview of its application in the SmartGrid and electric vehicles	Rahimi-Eichi, H., et al.	IEEE Industrial Electronics Magazine	460
8.	2010	Contribution of Li-Ion batteries to the environmental impact of electric vehicles	Notter, D.A., et al.	Environmental Science & Technology	439
9.	2014	State of charge estimation of lithium-ion batteries using the open-circuit voltage at various ambient temperatures	Xing, Y.J., et al.	Applied Energy	402
10.	2011	Adaptive unscented Kalman filtering for state-of-charge estimation of a lithium-ion battery for electric vehicles	Sun, F.C., et al.	Energy	377
11.	2014	A comparative study of commercial lithium-ion battery cycle-life in electric vehicle: Aging mechanism identification	Han, X.B., et al.	Journal of Power-Sources	341
12.	2016	Critical review of state of health estimation methods of Li-ion batteries for real applications	Berecibar, M., et al.	Renewable & Sustainable-Energy Reviews	336

Table 9. *Cont.*

S. No.	Publication Year	Documents Title	Author Name	Journal Name	Total Citation (<2021)
13.	2006	Sigma point Kalman filtering for battery management systems of LiPB-based HEV battery packs—Part 2: Simultaneous state and parameter estimation	Plett, G.L.	Journal of Power-Sources	335
14.	2011	Battery management system (BMS) and SOC development for electrical vehicles	Cheng, K.W.E., et al.	IEEE Transactions on Vehicular Technology	323
15.	2018	Critical review on the battery state of charge estimation methods for electric vehicles	Xiong, R., et al.	IEEE Access	318

There are many papers with repeated works with limited contributions. When reading a paper, first read the abstract and conclusion; if the topic and content are useful, then read the rest of the paper. While reading the whole paper, first go through the overview of the topics discussed in sections, figures/tables through that paper pattern, and the relevance of work is identified. In this way, we can identify the contribution of the paper. Every paper is unique in its own way. While doing the literature review, this process needs to be followed. The literature review gives a brief qualitative discussion of papers, their findings, their research gaps, the methodologies used in the paper, the comparison of different methods, and the applied methods. In contrast, the bibliometric review is a quantitative discussion of papers, authors, countries, year of publication, subject area, keywords, funding agency, journals, and affiliation. Figure 11 shows a critical analysis of the top-cited paper on SCOPUS and WOS. Highly cited authors provide more discussion on issues, challenges, and methods to overcome problems in lithium-ion battery BMS and SOC. Mostly since 2020, these papers are cited by other authors, which shows that researchers are most enthusiastic about this BMS and SOC topic. Battery SOH papers number 496 documents in SCOPUS and 1323 documents in WOS. At the same time, battery SOC papers number 2808 documents in SCOPUS and 7741 documents in WOS. The level of complexity to estimate SOH is more as compared to SOC. For instance, the estimation of SOH seems more difficult than SOC, but in reality, more publications deal with the latter issue. Much less research work has been done with regard to the challenges, issues, and state estimation methods for Li-ion battery, and BMS and SOC estimation.

Figures 12 and 13 show the graph trend of the top five documents in SCOPUS and WOS DB, respectively, in BMS EV state estimation.

The paper entitled "A review of lithium-ion battery state of charge estimation and management system in electric vehicle applications: Challenges and recommendations" had a steep increase in the number of citations in 2020 in SCOPUS DB. The paper entitled "A review on the key issues for lithium-ion battery management in electric vehicles" had a steep increase in the number of citations in 2020 in WOS DB. In Figure 12, we see that the paper entitled "State of-charge estimation of lithium-ion batteries using the open circuit voltage at various ambient temperature" initially had an overall higher citation rate than "Long short-term memory networks for accurate state-of-charge estimation of Li-ion batteries," but the latter paper has gathered more citations than the earlier paper over time. Similarly, in Figure 13, the second overall most cited document was highly cited in 2021. This shows that trend of highly cited papers changes every year. In that particular year whichever paper was more highly cited proved that it had some new informative content.

Source titles in SCOPUS and WOS DB are shown in Figures 14 and 15 respectively. Energies has a maximum 22% of publications and contributions in the state estimation of EV in SCOPUS DB followed by the Journal of Power Sources with 15% of publications. However, in the case of WOS DB, the Journal of Power Sources and Energies lead with 21% of publications, followed by Applied Energy with 12% of publications.

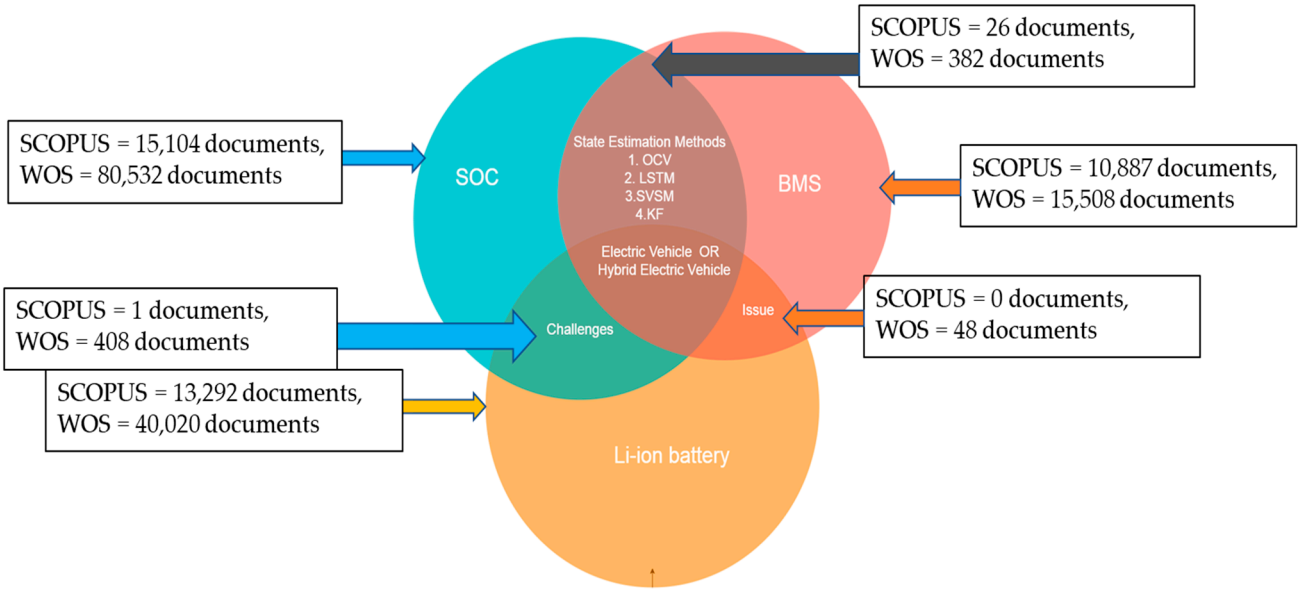

Figure 11. Critical analysis of top cited paper of SCOPUS and WOS.

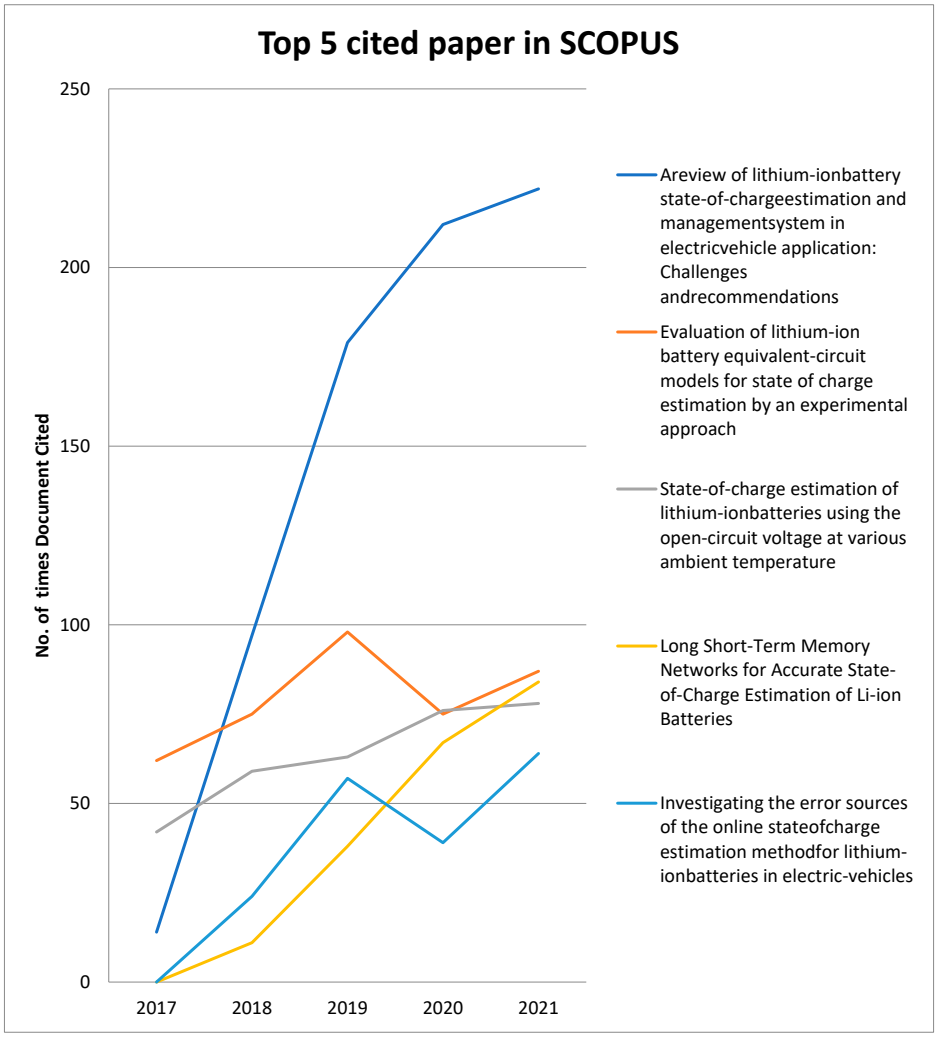

Figure 12. Top five cited papers of BMS EV across 5 years in SCOPUS DB.

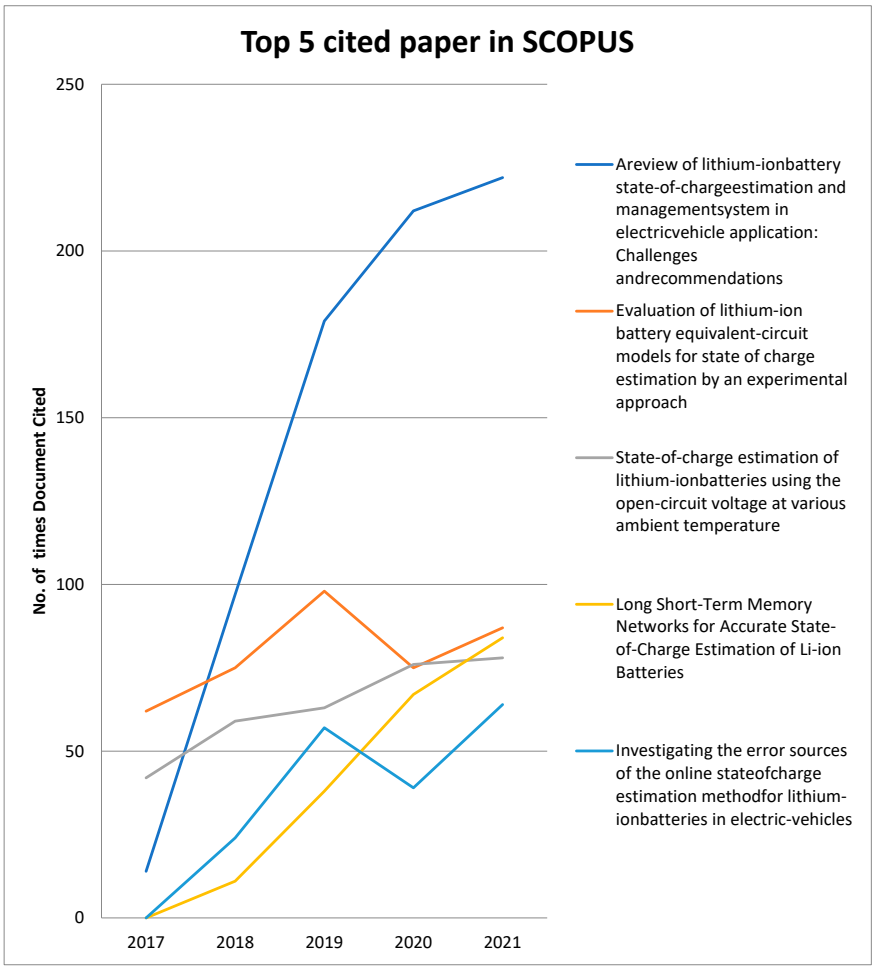

Figure 13. Top five cited papers of BMS EV across the last 5 years in WOS DB.

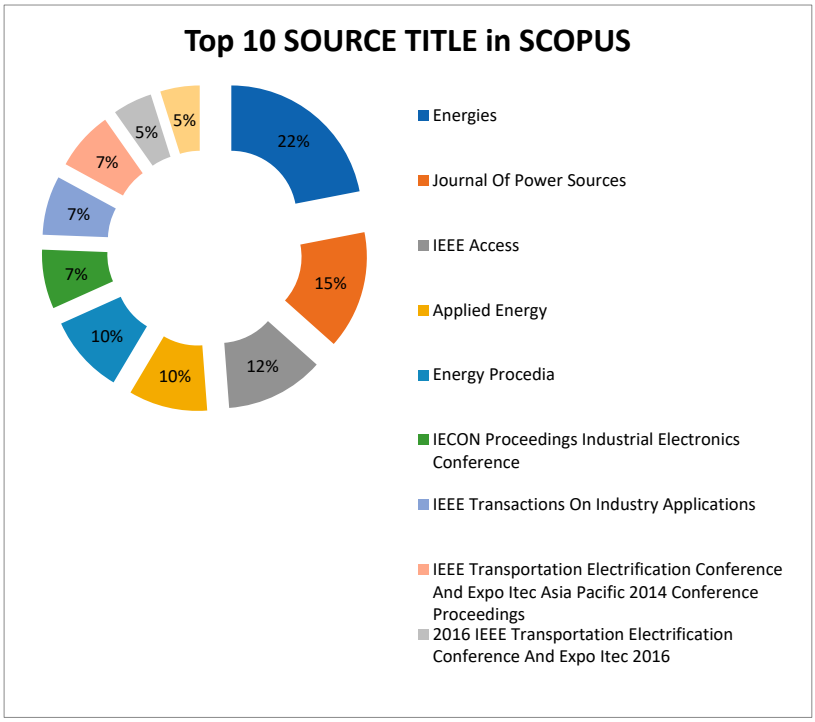

Figure 14. Top ten source titles in SCOPUS DB.

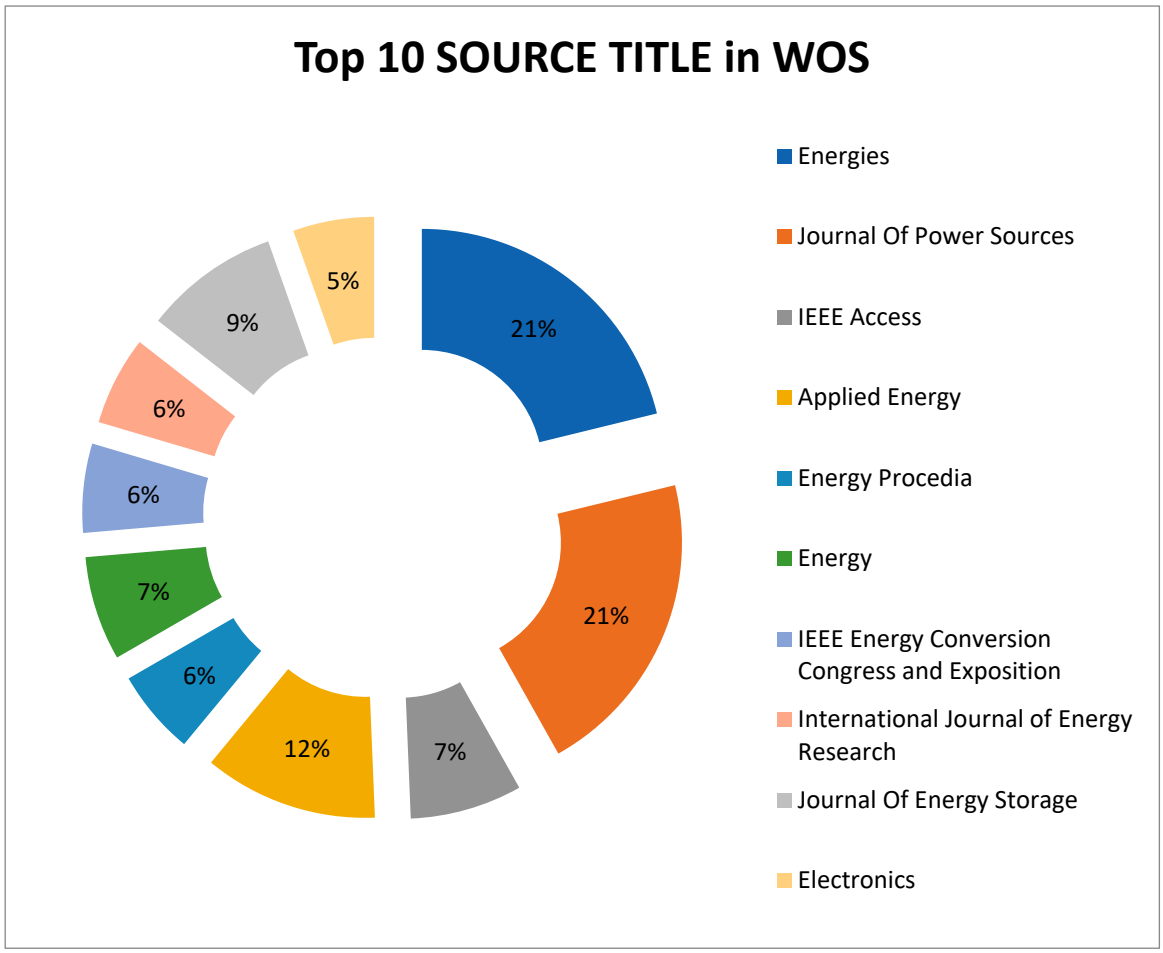

Figure 15. Top ten source titles in WOS DB.

Figure 16 shows maximum number of words used in the most cited paper. This visualization is created by using online the free software found at www.wordclouds.com (Accessed on 15 March 2022). In this software, a PDF document of a paper is uploaded, and this effect with a vehicle theme is created. The word "SOC" is repeated the most in this paper followed by "SOH", "model", "cell", "system", "sources", and "BMS".

Figure 16. Visualization of top cited paper words in "Wordcloud".

In Figure 17, GPS visualization using the www.gpsvisualizer.com (Accessed on 15 March 2022) tool helps to understand which countries are contributing the most toward research work in EV BMS state estimation. China leads in research work contributions and publications. Mostly Asian and Europeans countries are influencing the research work in EV BMS, followed by the USA and Australia. The research is mostly carried out in Asian and Western European countries.

Figure 17. GPS visualization of countries contributing to EV BMS state estimation.

Figure 18 shows the clustering of author and co-authorship in the SCOPUS DB. There are four clusters of authors and co-author relationships from the SCOPUS DB. R. Xiong has the most networks (13 links) between co-authors, followed by H. He with eight links. This cluster is generated by using VOSviewer open-source software. The minimum number of documents per author is two and a minimum of two citations per author is the criteria set for this analysis.

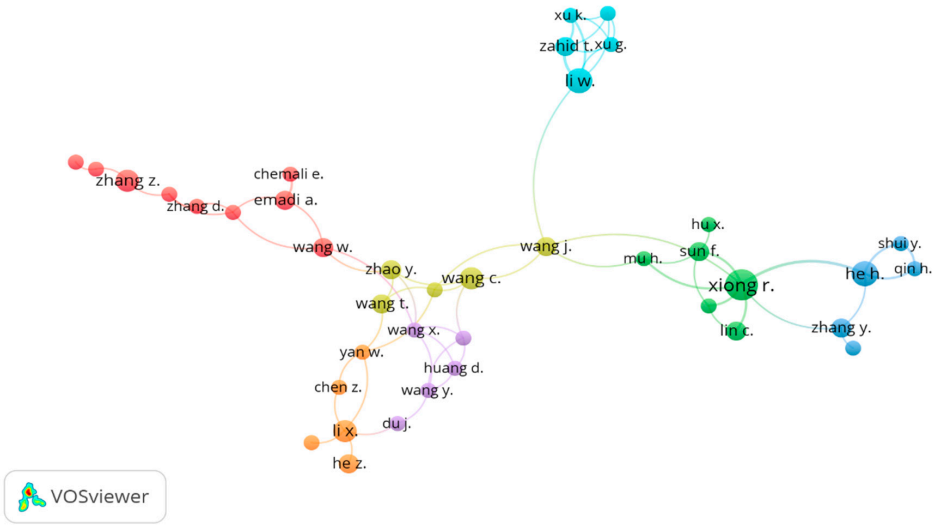

Figure 18. Cluster of co-authorship and author in the SCOPUS DB.

Figure 19 shows the clustering of author keywords and their occurrence in the SCOPUS DB. The "SOC estimation" keyword is big in size, which reflects that this keyword has a maximum occurrence of 47, and 96 links in different papers, followed by "electric vehicle", which has 31 occurrences and 94 links. Then "state of charge" has 29 occurrences and 72 links, and then "lithium-ion battery" has 23 occurrences and 56 links. The minimum number of occurrences of the keyword is chosen as two in VosViewer as the threshold.

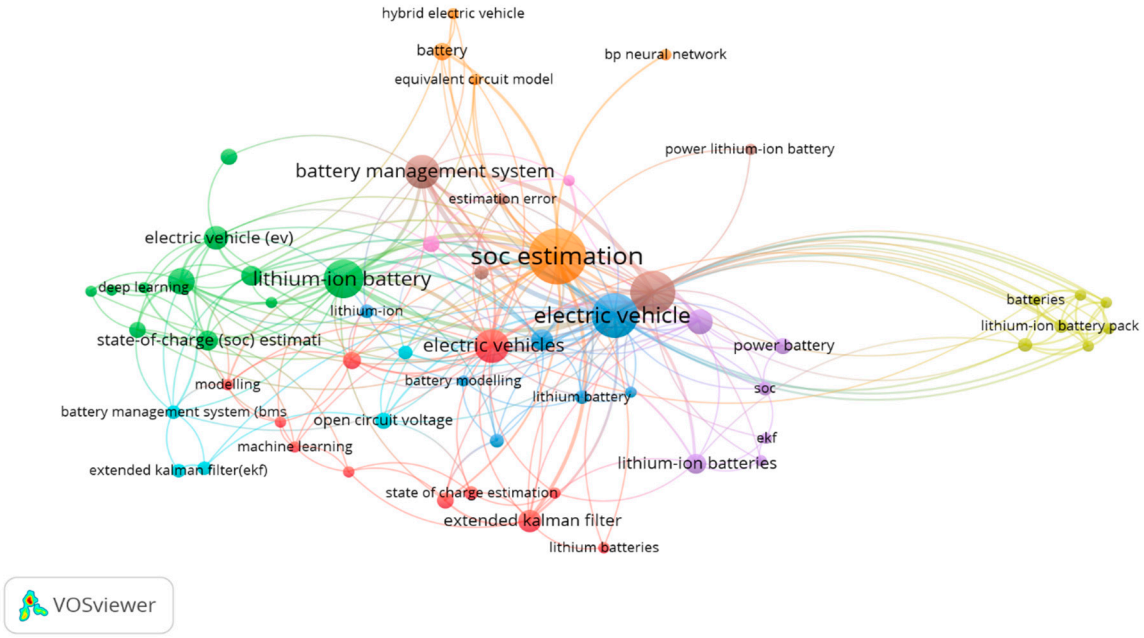

Figure 19. Mapping of authors' keyword and occurrence in the SCOPUS DB.

5. Challenges and Future Perspective

There are various issues related to lithium-ion batteries. Issues related to recycling lithium-ion batteries and pertinent environmental issues as well as manufacturing, utilizing, and end-of-life issues are discussed in [33]. In [34], the author discusses issues related to lithium-ion safety, accidents, existing technology, solid-state batteries, and causes in the lithium-ion battery at the cell level or pack level. Lithium-ion battery impedance varies with time, and temperature; therefore, proper modeling of lithium-ion battery in on-board vehicles is discussed in [35]. Different safety issues related to chemical reaction, thermal runaway [36], electrical–mechanical abuse, strategies and testing standard of lithium-ion batteries are discussed in [37]. Based on machine learning tools safety risk is predicted in [38]. The achievement of high accuracy in the prediction of cylindrical and pouch battery is another issue. After completion of the first life cycle of the lithium-ion battery, one can plan how to use it for a second life. These challenges are discussed in [39]. There are various new battery chemistries researched, and some of the latest popular batteries are the sodium-ion batteries [40], bio-inspired material for the secondary application of batteries [41], anionic battery [42], rechargeable Zn-air battery [43], potassium ion batteries [44], batteries related to particular applications such as EVs [45,46], non-aqueous, rechargeable aluminum batteries [47,48], and flexible zinc battery [49]. BMS plays a major role in state monitoring, energy management, communication between hardware and software and the protection of batteries from fault. The state estimation of batteries is a critical task for detection and handling. Early detection of sudden disturbances will save lives from severe danger. Batteries have to respond in milliseconds in order to prevent any hazardous activity. Data acquisition should respond quickly at high frequencies in order to provide accurate data online. Standardizing the charging mechanism and network protocol will help to simplify use cases. Giving more weight to the charging/discharging cycle, temperature change, resistance increase, and capacity fade will contribute to early detection of the fault. In the

future, a deep analysis of capacity fading due to low temperature and high cycling rates has to be investigated [50]. Capacity fade behavior due to deep discharge with different load conditions has to be analyzed. Much less research has been done on calendar aging batteries, and keeping batteries idle also reduces the capacity of a battery. Most of the research work has been done on the cell level, not on the battery-pack level, which can be explored as a part of a future work. There are various evolving terminologies related to EV battery SOC and SOH which need to be explored in depth in the future. These include "beginning of life" (BOL), "state of power" (SOP), "state of safety" (SOS), "remaining useful life" (RUL), and "end of life" (EOL). By knowing SOH, SOC can be determined and vice versa. By knowing SOC, SOP can be estimated and the remaining distance to travel to empty can be calculated. Challenges include the research gaps that can be fulfilled in the future, and by the help of this analysis, researchers will be able to refer to the latest papers of top authors and also ask for funding from a highly funding agency.

6. Concluding Remark

The bibliometric analysis is based on the recent trend in EV BMS with respect to author, citation, country, journal publication, and funding agency. Most of the bibliometric EV study has been done on policy frameworks, battery thermal management, and the overall development in the EV sector and the amount of research carried out on EVs. This paper's main aim is to discover the top ten authors, documents, journals, funding sponsors, affiliates, and countries in the field of state estimation of battery management system in EVs. This analysis will help researchers, industrialists and beginners to know who the top authors are and their research work. The published literature was sourced by SCOPUS and WOS database record, and the analysis was done through visualization tools. China leads in EV BMS research work, Xiong Rui and He Hongwen are the top authors. The *Journal of Power Sources* and *Energies* are the top journals. The National Natural Science Foundation of China is the top funding agency and "engineering" is the core subject area where this type of research is going on. The Chinese Academy of Sciences and Beijing Institute of Technology are the top affiliations. Very little research has been carried out on the state estimation of EV batteries. The statistical analysis of the top ten countries' productivity results is also discussed.

Online accurate data collection and prediction is necessary for the unforeseen nonlinear behavior of batteries. Sensors must give exact data and must be unaffected by noise emulsion. The capacity of batteries degrades over time, and manufacturers give a 5-year warranty in battery purchase but due to cycling and use case, the battery degrades before warranty time. In the future, developing an algorithm that detects health indications in a few cycles with less error will further improve overall battery life. BMS is tested in a laboratory-controlled environment so real-time dynamic environmental analysis of BMS plays significant role in developing good BMS. Integrating BMS data with the cloud will allow a large amount of data to be stored and analyzed better.

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