Exploring the global publications on varistors using the Scopus database through a bibliometric analysis

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ABSTRACT
The global increase in electrical device consumption has escalated the demand for excellent surge protectors. As a state-of-the-art technology, varistor has received considerable attention due to its outstanding versatility and wide range of applications. Hence, it is crucial to understand the development trend of varistor to expand the collaboration networks and propel its advancement. In this bibliometric article, several procedures were presented and analyzed to determine the global research trend of varistor based on the publication output each year, leading countries, most prolific authors, and co-occurrences of author keywords. After several stages of collecting and refining the textual information from the Scopus database, a total number of 2122 research articles and conference papers were retrieved between 1951 and 2021. Results show that since 1975, the annual number of publications has increased significantly, with 2020 recording the highest value of 1363 articles. China, the United States, South Korea, and Japan contributed around 60% of the total articles published. Moreover, three of the most prolific institutions associated with the research topic were ranked among the top 200 universities globally. The analysis of varistor research progress will provide a common overview of collaborative networks and potential collaborators for a better broadening of knowledge.

1. Introduction
It is recognized that the increased consumption of electrical energy because of frequent changes in individual lifestyles worldwide has driven the improvement of the electrical network of power lines [1]. Following this trend, the growing demand for better surge arresters and emerging industrialization have pushed researchers to evaluate different materials. The varistor ceramics used as a protection device inside the arrester assembly are highly efficient at adjusting and normalizing power consumption. These devices provide excellent protection for electronic appliances toward the damage caused by sudden voltage surges, ensuring their safety and reliability [2]. The device is commonly incorporated in various commercial, industrial, and household applications connected to either AC or DC power sources. According to global analysts, the consumption of surge arresters is expected to increase significantly between 2017 and 2025 [3]. Increases in power generation are likely to affect voltage arrester demand in the coming years. Concerns about dwindling energy resources are expected to lead to increased electricity generation from renewable sources, which will open up opportunities to deploy innovative technologies with these surge suppressors in the near future.

Due to its ability to respond quickly, less than 20 ns, the device can prevent transient surges. Hence, electronic equipment such as computers, handphones, laptops, tablets, and other modern electric or electronic devices required varistors to regulate the receiving voltage. The principles behind a working varistor are dependent on its nonlinear characteristics attributed to the structure of the grain boundaries [4]. Generally, grain boundaries fabricated through the addition of additives and dopants are composed of both conductive and non-conductive layers. These co-existing structures give rise to a barrier potential, known as the Schottky barrier, which can reduce or block the incoming overvoltage by trapping the electrons at their boundaries. As a protective device, the varistor diverts the current generated by the excessive voltage away from the sensitive components when it is triggered. Its function automatically compensates for resistance oscillations to provide a normalized transmission and reduce noise. The name varistor is thus a portmanteau of variable resistance. This term is used only for the nonlinear variable resistors.
Varistor ceramics have been extensively studied to protect transmission and distribution systems, electronic circuits, and low-voltage transients. The development of simpler semiconductor materials (e.g. single-phase) that require smaller amounts of dopants to achieve the desired varistor characteristics is one of the innovative technological innovations. This results in lower production costs and makes it easy to understand the functions performed by each additive used as a dopant. The varistor characteristics, controlled by the additives used individually or in combination, have prompted researchers to look for new systems based on other polycrystalline semiconducting materials.

Over the years, the worldwide publications on the topic of varistor have continued to increase. However, no article has been published to discuss its global publication trends based on the author’s knowledge. This paper examines the chronological trends of varistor research publications and displays the contributions of prolific authors, leading countries, and the most productive academic institutions. Our objectives are also intended to enlighten typical terms and subjects of the research area. We then identify countries according to their mastery of the main applications and give a point of view for future collaborations and directions. Understanding the current research trends in varistor will help researchers, policymakers, and individuals discover new research prospects in the near future.

2. Methods

A bibliometric study to understand the global progress of varistor is performed by examining the trends of publication from the earliest publication date recorded back in 1951 to 2021 from the Scopus database. This type of review gives a different perspective in understanding the importance of a research trend compared to the typical review article that primarily focuses on discussing the latest development and progress, as well as future recommendation of a specific research subject.

2.1. Data source and search strategy

The process of collecting data was performed between January 1 and January 4, 2022, utilizing the Scopus database. The main theme used to gather the articles was a refined based on the term “varistor” contained in both title and abstract, with the oldest article being published in 1951 and the latest from 2021. The key word search string was: (TITLE (varistor) AND ABS (varistor)) AND PUBYEAR > 1950 AND PUBYEAR < 2022 AND (LIMIT-TO (SRCTYPE,“j”)) OR LIMIT-TO (SRCTYPE,“p”)) AND (LIMIT-TO (DOCTYPE,“ar”) OR LIMIT-TO (DOCTYPE,“cp”)]. The search string initially generated a total of 2129 articles. An additional phrase was added to the search string in order to exclude review articles from our study, resulting in 7 articles being potentially irrelevant. In the title and abstract, this search string included phrases like review, recent, progress, critical, overview, bibliometric, and potentiometric. Using the EID of this review article, which is a unique article identity from Scopus, the next search string was created to ensure that only research articles remained. The final search string also excluded standard review articles, book chapters, and any potentially irrelevant studies so that only research articles were left. The process reduced the total publications to 2122 articles.

The data tabulated for the most productive journals were arranged according to the total publications produced in the selected timeline. Additionally, the single-country publication (SCP) information in the listing of the most productive countries and institutions was acquired using the keyword AFFILCOUNTRY to limit the search output toward each country. After collecting and organizing the findings from the central theme by year, source, author, affiliation, country, topic area of interest, and document type, the remaining publications were 2122 articles. Bibliometric data from the Scopus website, such as total publications and citations, CiteScore, and h-index, were also deployed to construct a more accurate ranking. Besides, to gain an insight into the trends in materials used to enhance varistor ability, a sub-theme was created based on the type of varistor-based ceramics and additives incorporated into varistor formulations. To acquire comprehensive information of the researchers’ interest in the varistor-based ceramics and the use of additives as varistor former, we also created two sub-themes (Figure 1), which were further subdivided into zinc oxide (ZnO), tin dioxide (SnO2), calcium copper titane (CaCu3Ti4O12) and silicon carbide (SiC) for the varistor-based ceramics, and bismuth oxide (Bi2O3), praseodymium oxide (Pr2O3), vanadium oxide (V2O5) and barium oxide (BaO) for the additives. It should be noted that the search string was executed separately for each material.

Furthermore, the search results of the sub-theme were modified from the previous search strings (2122 documents) by adding specific terms to find the type of application of interest such as (“zinc oxide” OR zn), due to the difference between the name and their chemical formula. The discussion of the sub-theme was reviewed based on the overall publications of the top five countries’ annual output publications. The general process of data mining and study elimination is shown in Figure 1, whereas the details of the central and sub-theme search strings are presented in Table S1 of the supplementary section.

2.2. Bibliometric maps

Bibliometric maps were constructed using 2122 publications in the Scopus database through the VOSviewer software (version 1.6.17, Centre for Science and Technology Studies, Leiden University, Netherlands).
Due to its broad compatibility with numerous databases, such as Scopus, Web of Science, Dimensions, Microsoft Academic, Lens, and PubMed, the software was chosen as a main tool for the analysis. VOSviewer displays the objects of interest, which represent the countries or author keywords that were used to create the bibliometric maps. The software helps determine the strength of the relationship between two items and displays it as numerical expressions that can be easily analyzed. For instance, if the connection between two items is stronger, the numerical value demonstrated in the link will be higher.

Through the extracted data of 2122 articles, two types of bibliometric maps focusing on coauthorship and co-occurrence were fabricated. Regarding the coauthorship maps, the link strength that connects the two countries was determined by the number of published articles containing authors affiliated with both countries. The overall strength of a particular country to other countries is referred to as total link strength. One of the limitations of using the VOSviewer software is that a detailed analysis of the relationships between countries can only be performed up to two countries or with all countries. Correspondingly, the link strength displayed in co-occurrence maps signifies the total frequency of articles when both search terms emerge together. The user guide for VOSviewer software can be found on the official website, which provides step-by-step instructions on how to use all of its features [5].

2.2.1. Analysis of coauthorship
This study includes all 56 countries associated with 3402 authors in the coauthorship assessment. The continents of Asia, Europe, America, Africa, and Oceania were used to group the countries. The maps were displayed using a full counting system in network visualization mode.

2.2.2. Analysis of co-occurrence
The author keywords in the article were used in the co-occurrence study and did not include indexed keywords generated by the Scopus database. From the analysis performed on the collected author keywords, a total of 2193 keywords from 2122 articles were produced. The fabrication of co-occurrence maps began by inserting the author keywords into the VOSviewer after it was filtered to ensure no redundancy occurred. For instance, keywords including Zinc Oxide Varistors, ZnO Varistor Ceramics, ZnO Ceramics, and ZnO Varistors were re-labeled as ZnO Varistor. The process yielded 2139 keywords, which were then used to create the maps. Due to the large number of keywords, the minimum co-occurrence value was fixed to 5 (the default setting), with 87 keywords being produced. The maps that were constructed were displayed in overlay visualization mode, and the color of the items and the strength of the links signify the average quantity of published articles annually that contained the keywords that have been chosen for inclusion.

2.3. Varistor-based ceramics and additives
A comparative analysis to study the trends and popularity of different types of varistor-based ceramics and additives was conducted by investigating both the central theme (keyword co-occurrences) and sub-themes (total number of publications). Bismuth oxide, for instance, is a popular additive and is commonly used in this field. As such, specific modifications in the search string to find all articles that contained the keyword “bismuth oxide” were required. The leading countries were identified based on their respective amount of publications that were related to the topic of interest.

3. Results and discussion
3.1. Trend in research interest and publication output
In the span of 71 years, 2122 research articles have been published pertaining to the research topic of the varistor. As shown in Figure 2, the research interest in the varistor topic increased a bit in 1968. After that, an
increment in publication output occurred in 1971 before dwindling from 1972 to 1974. It is noticed that substantial interest in varistor research began in 1975. It is suggested that a substantial increase in the topic began after its lowest point from 1972 to 1974, where only 1 article was published. From that point onward, a rapid increment signifying an increasing awareness of the importance of varistors was recorded. Besides, it was discovered that the quantity of articles generated increased by almost 10 and above per year from 1975 to the end of 1989. From 1989 onwards, the annual growth rate (AGR) increased by 100% in the subsequent one and two years. Although there was a minor drop in the annual number of published articles, it was discerned that a spike in the number of articles published was recorded after this period of reduction. The small but consistent annual publications throughout the year have produced a large cumulative total publication. It is expected that the number will push on for years to come as the awareness in the researcher’s community continues to grow. Unfortunately, one of the drawbacks perceived by the author is that most of the articles are not published in open access, making it harder for more researchers to recognize the significance of varistor as a surge protector to protect their electronic devices. To date, only 10.18% (216 articles) were published in open access. Thus, to exponentially increase the number of citations with wider accessibility, we proposed that more articles are to be published in open-access.

Varistor research involves a wide range of research areas, and many research groups around the world are working on these topics. According to subject area analysis, the primary focus of varistor studies is in materials science. On the other hand, the analysis of the collected articles’ subject areas displayed that most researchers classified the varistor studies under Materials Science. This is evident according to the total published articles of the subject area, which has reached 1382 articles, followed by Engineering (1141 articles), Physics and Astronomy (912 articles), Chemical Engineering (160 articles), and energy (158 articles). Varistor research has gained attention due to its extensive use of semiconductor ceramics as varistor-based ceramics. Research on varistor ceramics started in 1969, when a varistor system based on ZnO emerged in Japan, owning very superior properties in comparison to those presented by SiC [6,7]. Other new materials are also being opted for by scientists to improve stability and seek alternative applications, which can stimulate new technology practice. S. A. Pianaro discovered in 1995 that varistor systems based on SnO2 exhibit nonlinear electrical properties comparable to ZnO varistors but with better thermal conductivity [8]. This discovery made it clear that SnO2-based varistor can play a vital role and match the efficiency of ZnO-based varistor or even higher. Other than that, another different type of varistor system available nowadays is the CaCu3Ti4O12 based varistor ceramics with a complex perovskite structure. It possesses a strong nonlinear behavior, which is even greater than that of ZnO varistor material [9]. As a reason, CaCu3Ti4O12 based varistor systems are one of the most crucial materials to be used as a surge protector in electronic devices due to their remarkable electrical properties.

Moreover, results based on the Scopus database also displayed that a number of articles included in this study have been published in languages other than English. For instance, the number of articles published in English was 1839 articles, followed by Chinese (205 articles), Japanese (31 articles), Russian (10 articles), German, Portuguese, Polish, Spanish, Korean, 

![Figure 2. The number of varistor research articles indexed in Scopus annually and cumulatively from 1951 to 2021.](image-url)
French, Romanian, Turkish, Moldavian, Moldovan, and Slovenian in less than 10 articles individually. Although the majority of these articles are not in English, for them to be indexed in Scopus, the title and abstract must be in English.

### 3.2. Preferred journals

Based on the collected data on the top 10 most prolific journals in Table 1, it was found that these journals were owned by six different publishers. The publisher with the highest number of journals listed was Elsevier. In total, there were four journals under Elsevier, which are “Ceramics International”, “European Ceramic Society”, “Materials Letters” and “Journal of Alloys and Compounds.” The other six journals were published by Wiley, American Institute of Physics, Springer Nature, Dianzi Gongye Bu, and Chongqing Yibiao Cailiao Yanjiusuo/Chongqing Instrument Materials Research Institute. The journal with the most output was Ceramics International with 126 articles, contributing 5.9% of the total publications, followed by Journal of The American Ceramic Society (107 articles; 5.0%), Journal of Applied Physics (102 articles; 4.8%), Journal of Materials Science Materials in Electronics (102 articles, 4.8%), Journal of The European Ceramic Society (97 articles, 4.6%) and the rest of the journals contributed below 60 articles. Although Journal of Applied Physics was placed on 3rd rank, it managed to achieve the highest number of total citations of 6107. Unfortunately, even though Journal of Applied Physics had the highest number of total citations, their article with highest number of citations published in 1979 received only 405 citations compared to the Journal of American Ceramic Society, which had 1417 citations, placing it on the 2nd rank. Meanwhile, Gongneng Cailiao Journal of Functional Materials published the least cited article with only six citations, placing it on the 10th rank.

According to the result, in terms of the CiteScore 2020, there were six journals with an average CiteScore above 5. Albeit placed on the 8th rank in the list, the Journal of Alloys and Compounds managed to secure the highest CiteScore at 8.9 compared to other journals. The journal with the lowest CiteScore was “Gongneng Cailiao Journal of Functional Materials” (0.3), which can be attributed to the journal’s primary language that is Chinese, causing it to be less popular among most researchers, with English as their main language. It is believed that some researchers use CiteScore as an indicator or measuring scale to determine the amount of “audience” that a journal may receive each year. Therefore, it is understandable that the importance of CiteScore to authors when selecting a journal to publish their work has a significant impact. As an alternate database to the Clarivate Analytics Impact Factor, CiteScore measures a journal influence by collecting and comparing the citation information of the Scopus database. Nevertheless, CiteScore should not be the only way to analyze a journal. Apart from

| Rank | Journal | TP (%) | TC | CiteScore (year) | The most cited article (reference) | Times cited | Publisher |
|------|---------|--------|----|-----------------|------------------------------------|-------------|-----------|
| 1    | Ceramics International | 5.9 | 2013 | 6.9 (2020) | Microstructure and electric properties of a SnO2 based varistor [10] | 94 | Elsevier |
| 2    | Journal of The American Ceramic Society | 5.0 | 5528 | 6.1 (2020) | Application of Zinc Oxide Varistors [11] | 1417 | Wiley |
| 3    | Journal of Applied Physics | 4.8 | 6107 | 4.4 (2020) | Theory of conduction in ZnO varistors [12] | 405 | American Institute of Physics |
| 4    | Journal of Materials Science Materials in Electronics | 4.8 | 999 | 4.0 (2020) | Dependence of non-linearity coefficients on transition metal oxide concentration in simplified compositions of ZnO+Bi2O3+MO varistor ceramics (M=Co or Mn) [13] | 43 | Springer Nature |
| 5    | Journal of The European Ceramic Society | 4.6 | 2289 | 8.2 (2020) | Microstructure and electrical properties of ZnO-Bi2O3-based varistor ceramics by different sintering processes [14] | 108 | Elsevier |
| 6    | Journal of Materials Science | 2.5 | 1446 | 6.7 (2020) | A grain-boundary defect model for instability/stability of a ZnO varistor [15] | 327 | Springer Nature |
| 7    | Materials Letters | 2.4 | 1014 | 5.8 (2020) | The nonlinear properties and stability of ZnO-P3rO5:CoO-Cr2O3-Er2O3 ceramic varistors [16] | 120 | Elsevier |
| 8    | Journal of Alloys and Compounds | 1.5 | 556 | 8.9 (2020) | Effect of TiO2 doping on microstructural and electrical properties of ZnO-P3rO5-based varistor ceramics [17] | 51 | Elsevier |
| 9    | Yadian Yu Shengguang Piezoelectrics and Acoustoacoustics | 1.5 | 41 | 0.4 (2020) | Studies of secondary phases in (La, Nb) codoped TiO2 varistors ceramics [18] | 8 | Dianzi Gongye Bu |
| 10   | Gongneng Cailiao Journal of Functional Materials | 1.4 | 32 | 0.3 (2020) | Preparation of low voltage ZnO-based varistor by spray pyrolysis and the study of dependence between the thickness and nonlinear characteristics [19] | 6 | Chongqing Yibiao Cailiao Yanjiusuo/Chongqing Instrument Materials Research Institute |

**Table 1.** The top 10 most productive journals on varistor research with their most cited articles from 1951 to 2021.

| TP: total publications; TC: total citations. |
CiteScore, consideration on whether the journal is capable of delivering their work to the relevant audience and contributing to progression in their field were also necessary.

### 3.3. Leading countries and top institutions

Figure 3 depicts the top 15 most prolific countries that have contributed the most to the development of varistor research area. Around 60% of worldwide publications were attributed to China, the United States, South Korea, and Japan, indicating that these three countries are significant contributors to the topic of interest. China was determined to be the most productive country, with 714 publications in 217 journals, representing 34% of all publications worldwide. In the total publication of a given country (TPc), South Korea was placed as the third most productive country after the United States and China. Even though the total publications (TPc) from South Korea were lower than that of the United States and China, it should be emphasized that the most productive academic institution, Xi’an Jiaotong University and General Electric (GE) Global Research, has a lower total publication of a given academic institution (TPI) than Dong Eui University, and also the academic institution from South Korea has the highest total publication (TPI) among the most productive institutions listed on the top 15.

Among the listed countries, there were only two countries that have less than 2/3 single country publications (SCP), which are the United Kingdom (61.1%) and Mexico (50.0%). A country with high SCP values shows a strong intra-country collaboration. This indicates that the majority of the country’s publications have authors who are only affiliated with one country. To rephrase it, authors from other countries are not involved in their publications. Despite having the least SCP, the United Kingdom and Mexico showed that their country has extensive international collaborations. Some of the main advantages of possessing a wide range of international collaborations are the expansion of network, sharing of theoretical and practical knowledge and as a constructive strategy to increase the university ranking. Taiwan has the highest SCP with 100%, where all of 63 publications are only from their country without involving any other countries. Although Mexico has the lowest SCP values at 50%, 50% (16 articles) of its publications were international collaborative papers involving 7 countries, placing it 15th among the most productive countries. In addition to Figure 3, the top 15 most productive institutions include the three universities listed in the top 200 best universities based on the 2021 World University Rankings – The University of Manchester (ranked 27th), Universiti Putra Malaysia (132nd), and the Indian Institute of Science (ranked 185th). This shows that the research interest in varistors has gained the attention and recognition from the top universities in the world.

Figure 4 displays the arrangement of countries following their respective regions. In VOSviewer, the link between the two countries indicates that they are related, which can be seen by their distance and thickness that correlates with the degree of collaborative works in varistor research. As the distance between the two countries is shorter, the relations between them in terms of the collaborative publications become stronger. Similarly, when the line is thicker, the links between them are higher. As shown from Figure 4, the red items stand for Asian countries, while the green items represent Europe, the blue ones represent America, the yellow items represent Africa, and the purple items represent Oceania. The number of countries according to their respective continents that contributed to varistor research area is as follows: Europe (25), Asia (18), America (8), Africa (4), and Oceania (1). The analysis of coauthorship demonstrated that the United Kingdom had the highest affiliation linked to 15 countries with 31 times of coauthorship. The list was followed by China (14 links, 70 coauthorships), the United States (13 links, 58 coauthorships), Brazil (10 links, 29 coauthorships), and Slovenia (10 links, 17 coauthorships). Likewise, among the 51 countries found in the database, more than 60% of them have published articles less than 10 with a collaborative partner from other countries.

There are several elements that can affect the strength of an international collaboration of a country such as the range of network of a researcher with others of foreign countries, visiting researchers, international grants, foreign postgraduate students and more. Hence, improving and increasing the variables that can contribute to these elements will play a major role in establishing a flexible and dynamic research project that can give excellent outputs and benefits in the future.

### 3.4. Leading authors

The list of the most prolific authors in the varistor research field is tabulated in Table 2. According to the data, among the 15 listed authors, 9 of them were affiliated to China, followed by Brazil (3 authors), South Korea (1 author), the United States (1 author), and Slovenia (1 author). The range of the first publication was between 1985 and 2005, with 6 authors having the roles as the first author and 9 authors as a coauthor. Although there are no specific rules in determining the arrangement, the last authors are usually placed as the corresponding authors. It would also be up to the readers to decide whether the total
number of citations, the h-index, or some other criterion should be used to determine the quality of an article. An author’s productivity and contribution impact of their works on a particular research topic is generally appraised by the h-index value.

C.W. Nahm from South Korea was ranked at the top with the highest number of publications, 118 articles since the year 2000, total cited time, 1807 citations with a h-index of 24. The second and third authors, J. Hu and J. He are both from the same academic institution, which is Tsinghua University, China, with a different year of first publication. Researchers from Xi’an Jiaotong University, China ranked 5th (S. Li) and 6th (J. Li). W.B. Su, J.F. Wang, and H.C. Chen from China were affiliated with the same institute, Shandong University, and published their first articles in the same year, 2000. Another pair from China is G.Z. Zang (9th) and G. Li (13th), but both are affiliated with different institutions, Henan University of Science and Technology and Shanghai Institute of Ceramics, Chinese Academy of Sciences.

Even though placed at the fourth position, J.A. Varela from Brazil has been cited more times in 1479 citations, while J. Hu and J. He only acquired 744 and 723 citations, respectively. A similar case was also observed for E. Longo at the seventh position, who secured the third-highest times cited at 1338 citations. Relatedly, P.R. Bueno from Brazil also has the fourth-highest with 857 times citations despite being placed in the fifteenth position. It is also necessary to notice that the authors mentioned in Table 2 do not necessarily appear in Table 1. The names will only be listed on both tables if the authors managed to publish articles that have been well received, such as C.W. Nahm, whose articles were placed at the seventh position in Table 1.
Table 2. List of the most prolific authors in the field of varistor research.

| Author              | Scopus author ID | Year of 1st publication | TP | h-index | TC    | Current affiliation                                      | Country               |
|---------------------|------------------|-------------------------|----|---------|-------|----------------------------------------------------------|-----------------------|
| Nahm, Choonwoo      | 7,003,981,828    | 2000 *                  | 118 | 24      | 1807  | Dong Eui University, Busan, South Korea                 | South Korea           |
| Hu, Jun             | 57,131,644,000   | 2005 *                  | 58  | 16      | 744   | Tsinghua University, Beijing, China                    | China                 |
| He, Jinliang        | 7,404,984,708    | 1996 *                  | 56  | 17      | 723   | Tsinghua University, Beijing, China                    | China                 |
| Varela, J. A.       | 7,102,462,077    | 1992 *                  | 51  | 24      | 1479  | Universidade Estadual Paulista Júlio de Mesquita Filho, Sao Paulo, Brazil |
| Li, Shengtao        | 56,338,373,700   | 1992 *                  | 44  | 13      | 438   | Xi'an Jiaotong University, Xi'an, China                 | China                 |
| Li, Jianying        | 55,917,982,100   | 2000 *                  | 42  | 14      | 483   | Xi'an Jiaotong University, Xi'an, China                 | China                 |
| Longo da Silva, Elson| 7,103,022,316    | 1992 *                  | 42  | 20      | 1338  | Universidade Federal de Sao Carlos, Sao Carlos, Brazil  | Brazil                |
| Su, Wenbin          | 7,402,010,109    | 2000 *                  | 35  | 14      | 513   | Shandong University, Jinan, China                      | China                 |
| Zang, Guozhong      | 7,004,525,807    | 2002 *                  | 35  | 13      | 392   | Henan University of Science and Technology, Luoyang, China |
| Wang, Jinfeng       | 55,742,600,900   | 2000 *                  | 34  | 14      | 459   | Shandong University, Jinan, China                      | China                 |
| Alim, Mohamad A.    | 56,847,056,500   | 1985 *                  | 31  | 15      | 708   | Alabama A and M University, Huntsville, United States   | United States         |
| Chen, Hongchun Cun  | 7,501,626,343    | 2000 *                  | 31  | 14      | 490   | Shandong University, Jinan, China                      | China                 |
| Li, Guorong         | 8,853,204,700    | 1998 *                  | 25  | 11      | 369   | Shanghai Institute of Ceramics Chinese Academy of Sciences, Shanghai, China |
| Bernik, Slavko      | 7,003,824,288    | 1999 *                  | 24  | 13      | 616   | Jozef Stefan Institute, Ljubljana, Slovenia            | Slovenia              |
| Bueno, Paulo Roberto| 7,004,575,077    | 1998 *                  | 23  | 16      | 857   | Universidade Estadual Paulista Júlio de Mesquita Filho, Sao Paulo, Brazil |

* Role in co--authorship, superscripts.
* First author.
* Coauthor.

The distribution of the authors corresponding to the particular use of the varistor-based ceramics is indicated in Figure 5. The number of authors was induced according to their preference for varistor-based materials. In the coauthorship analysis, the authors are clustered regarding their use of varistor-based ceramic materials. As can be seen in Figure 5, red stands for zinc oxide (ZnO), while green stands for tin dioxide (SnO2), blue stands for titanium dioxide (TiO2), yellow stands for tungsten trioxide (WO3), purple stands for strontium titanate (SrTiO3), orange stands for calcium copper titanate (CaCu3Ti4O12) and black stands for silicon carbide (SiC). From a total of 3402 authors, the authors with the greatest total link strength were selected, which consisted of 1000 authors. After re-labeling similar possible authors, only 705 items with the largest set of connected authors were detected by VOSviewer software. A total of 705 authors were recorded, among them 526 who were dominated by ZnO, followed by SnO2 (110 authors), TiO2 (49 authors), WO3 (3 authors), SrTiO3 (7 authors), CaCu3Ti4O12 (9 authors), and SiC (1 author). In addition, the authors’ cluster networks were arranged by
3.5.1. Terminology

The re-labeling of continents, as shown in Figure 6. The highest number of authors per region came from Asia (509 authors), followed by America (101 authors), Europe (92 authors), and Africa (3 authors).

3.5. Author keywords

Out of a total of 2139 author keywords, only 87 were selected for the mapping in VOSviewer software after re-labeling similar and congeneric terms and selecting the minimum number of occurrences at the default value of 5.

3.5.1. Terminology and concept

According to the mapping in Figure 7, we found that “Varistor” is the most frequently appeared author keyword with 522 occurrences and 79 links to other related keywords. Terms’ Electrical Properties’ follow the list (344 occurrences; 59 links), “ZnO Varistor” (267 occurrences; 62 links), “Zinc oxide” (240 occurrences; 63 links), “Microstructure” (162 occurrences; 53 links), “Ceramic” (81 occurrences; 33 links), and “Sintering” (75 occurrences; 34 links). Additionally, our results showed several keywords attributed to the measurement of varistor’s performance, including Nonlinear Coefficient (56 occurrences), Breakdown Voltage (35), Dielectric Properties (29 occurrences), Leakage Current (19), Grain Size (16 occurrences), I–V Characteristics (10), and Barrier Height (6 occurrences).

It is also interesting to see several materials as author keywords, which were generally used in the fabrication process as additives or dopants to enhance the varistor’s nonlinear properties. The materials that appeared in the list were bismuth oxide, Bi₂O₃ (8), praseodymium oxide, Pr₂O₁₁ (12), Chromium oxide, Cr₂O₃ (7), Antimony trioxide, Sb₂O₃ (8), Titanium dioxide, TiO₂ (49), Copper oxide, CuO (5), Dysprosium oxide, Dy₂O₃ (7), Tantalum oxide, Ta₂O₅ (6), and Yttrium oxide, Y₂O₃ (7). Moreover, it was discovered that one of the most popular trends in this research topic was the study of multiple dopants/additives effects on varistor’s efficiency. For example, Meng et al. [20] used multiple dopants and indicated an improved nonlinearity (α) of the varistor. Another example by Hembram et al. [21] fabricated a varistor with several dopants and successfully produced a varistor with an α value of 95.

The term “ZnO Varistor” has been widely used as an author keyword due to its simplicity and versatility as varistor-based ceramics. The performance of ZnO varistors can be altered by varying the percentages and compositions of the additives. Since the discovery of excellent nonlinear electrical properties of ZnO varistor by Matsuoka in 1969, various research groups have focused on the conduction mechanism in the ZnO varistor [22]. To date, numerous additives with the purpose of improving the electrical characteristics of varistors were tested, with the processing parameters improved in the first decade after Matsuoka’s invention. Thus, it is essential for any researcher to find a suitable additive or dopant to enhance the nonlinear electrical performance of the varistor for their desired application.

Furthermore, several keywords devoted to the instruments and techniques used for the analysis purpose were also discovered. Some of which involved “DC Accelerated Aging Stress” (11 occurrences), “High-
Energy Ball Milling” (10 occurrences), “Impedance Spectroscopy” (9 occurrences), “Scanning Electron Microscope” (9 occurrences), and “X-Ray Diffraction” (5 occurrences). Along with “ZnO Varistor,” other terms for the varistor-based ceramics were also applicable, such as “SnO₂ Varistor” (9 occurrences) and “TiO₂ Varistor” (7 occurrences).

3.5.2. Topics of interest

The improvement of varistor performance has emerged as an evolutionary technology to obtain higher stability with various possibilities of new applications. Keywords containing “Nonlinear Coefficient” were repeated 56 times from the collected database, which identifies the performance of a varistor. The
nonlinear coefficient is the ultimate parameter to measure the protection power of the varistor component and how fast it can absorb the dangerous surge in transient voltage [23]. A varistor contains a ceramic mass of conductive grains and non-conductive grain boundary layers. The grain boundary (49 occurrences) between each grain consists of double Schottky barriers (25 occurrences) that can conduct significantly increased current when voltage surge occurred [24]. Nonlinearity performance of varistors results from the existence of potential barriers at the inter-grain boundaries [25]. The other three significant parameters that determine the varistor characteristics are breakdown voltage, leakage current, and barrier height, where their keywords were repeated 35, 19, and 6 times, respectively. Varistor with high nonlinear coefficients ($\alpha$), desirable nonlinear voltage ratings ($V_b$), low leakage current values ($I_c$), long lifetimes, and high energy absorption capacities are the preferable options.

The fabrication of varistor ceramics commonly involves two methods, first by identifying a suitable preparation technique to obtain ceramic powders with better physical properties for specific applications and second by mixing varistor-based ceramic powders with several possible additives or dopants to enhance both their microstructure and electrical properties. It is important to emphasize that the characteristics of varistor devices are directly depending on their microstructure. This microstructure, on the other hand, is regulated by the distribution of grain size, grain boundaries, secondary phases, and pores [26]. The keywords associated with “Microstructure” were repeated 162 times, which indicates that most of the researchers discussed the mechanism of varistor characteristics based on their microstructure properties. A breakdown voltage phenomenon occurs due to modification in grain size within the microstructure of varistors, which differentiate the difference between the application of low and high voltage varistors. Varistors have been broadly applied in the electrical system as surge protection devices over a wide voltage range, starting with a few volts for low voltage varistors in miniature devices to tens of kilovolts for high voltage varistors in transmission lines and distribution networks [27].

Since the implementation of electronic circuitry into IC chips has led to considerable size and weight reductions, the demand for varistors in the application of low voltage has also increased. The use of the “Low voltage varistor” term was appeared 25 times and linked to 22 other keywords. This is evidenced that multiple researchers have been working on the development of miniaturized varistors and have started to focus on improving their performance. Miniaturized varistors with small grain size, high breakdown voltage, high nonlinearity, and low leakage current need to be fulfilled to achieve high-performance low voltage varistors [28]. For low voltage varistors, TiO$_2$ is a dopant that is usually used to enhance the grain growth of varistors by reducing the number of grains in series between electrodes, whereas the breakdown voltage is proportional to the number of grains within the structure of varistor ceramics [29]. It has been found that “TiO$_2$” has been used 49 times as author keywords. In the typical microstructure of varistors, Bi$_2$O$_3$ is used as an additive that presents as a secondary phase and promotes potential barriers to electrical conduction at the interface of grain boundaries [30]. The term related to “Bi$_2$O$_3$” was perceived 8 times in author keywords, displaying that the selection of Bi$_2$O$_3$ as an additive has become more common.

Commercially, a solid-state preparation approach is deployed to mass-produce varistors. The primary processes of this method involve powder preparation, mixing, pre-sintering, milling, sieving, pressing, sintering, silvering, and testing. The two critical stages in the process that govern the electrical characteristics of varistors are the preparation of raw ceramic powders and sintering temperatures. Even though the solid-state route remains the preferred industrial method because of its simplicity and cost-effectiveness, a drawback of this route is the difficulty to obtain microstructure homogeneity, a particularly essential aspect for the manufacture of miniaturized devices in modern electronic and communication appliances. Varistors fabricated via this technique also require high sintering temperature and prolonged sintering time, leading to excessive grain growth while inducing unwanted reactive phases with low stability. Keywords containing “Sintering,” “Grain growth,” and “Stability” have been discussed 75, 16, 19 times, respectively, which signify that these terms have a significant effect on varistor properties. In order to prepare high-quality varistor powders, researchers have introduced a wet chemical technique to overcome the disadvantages of the solid-state processing method. The benefits of wet chemical processing are better purity and homogeneity and a lower processing temperature. One of the most frequently used wet chemical techniques is “Co-precipitation,” and its term has been encountered 8 times in the database. The demand for power system safety and stability has grown in recent years. Higher specifications for varistors in terms of electrical property stability against AC accelerated aging is required, whereas the unstable electrical performance can restrict their energy absorption capability [31]. When the performance of a varistor is weak, the reliability and stability of surge arresters will degrade during operation. The efforts toward enhancement of varistor performance can be seen from keywords’ Aging’ (16 occurrences), “Degradation” (46 occurrences), and “Energy absorption capability” (18 occurrences).
3.6. Distribution of varistor publications upon the use of the varistor-based ceramics and additives

Regarding the number of articles and author-keywords occurrences, there was a significant relationship between the sub-theme and central theme search outputs. The analysis of Figure 8 depicts that ZnO and Bi$_2$O$_3$ are the most popular varistor-based ceramic powders and additives in the varistor research community, with higher values of 1293 and 166 articles, respectively. From the total of 2122 research articles, the publications include ZnO and Bi$_2$O$_3$ as the basic substance, containing 61% and 7.8% of the total global publications, respectively. For the varistor-based ceramics, the list was followed by SnO$_2$ (138 articles), CaCu$_3$Ti$_4$O$_{12}$ (9 articles), and SiC (7 articles). Contrarily, for the additives, it was followed by Pr$_6$O$_{11}$ (87 articles), V$_2$O$_5$ (79 articles), and BaO (24 articles).

The implementation of ZnO in varistor research fields began to gain popularity in 1975, and since then, it has become the most frequently used as

![Figure 8](image8.png)  
**Figure 8.** Research progress of the designated varistor-based ceramics and additives.

![Figure 9](image9.png)  
**Figure 9.** Top five countries based on the number of publications of the designated varistor-based ceramics and additives.
varistor-based ceramic powders. Due to their highly nonlinear characteristics and excellent surge withstand capability, ZnO-based ceramic varistors are primarily used in circuits to protect against transient surge voltages [32]. Many years ago, varistors made of silicon carbide ceramics were used to protect electronic circuits from surges. However, their nonlinearity is not strong enough to protect the circuits. While other varistors based on SnO\textsubscript{2} and CaCu\textsubscript{2}Ti\textsubscript{4}O\textsubscript{12} are being investigated to replace the ZnO varistor, it remains as the most popular type of varistor for a variety of applications ranging from small current electronic circuits to large current transmission lines [33].

As for varistor formers, Bi\textsubscript{2}O\textsubscript{3} started getting attention in 1980, and after that, its popularity escalated until it became the most commercialized additive for varistor materials. Bi\textsubscript{2}O\textsubscript{3} is the most common component in creating the electrostatic barrier in the microstructure of varistors for forming the nonlinear behavior [34]. However, in the manufacture of multilayer chip varistors with low-voltage characteristics, Bi\textsubscript{2}O\textsubscript{3} is not suitable due to their high volatility and reactivity during the sintering process [35]. In order to overcome the limitations of Bi\textsubscript{2}O\textsubscript{3}-based ZnO varistors, the addition of other oxides, such as Pr\textsubscript{6}O\textsubscript{11}, V\textsubscript{2}O\textsubscript{5}, and BaO have been introduced to perform varistor behavior which exhibits simple microstructure with better nonlinear electrical performance [36–38].

Additionally, the link strength of the two keywords can be used to assess research interest in specific areas. For instance, the keyword “Varistor” was linked to 79 other keywords, including “Sintering”, “Degradation”, and “Dopant”. As indicated by the link strength of 48 for varistor–sintering and 19 for varistor–degradation, it is suggested that research interest in varistor–sintering was greater than that in varistor–degradation. The stronger link strength of sintering and degradation terms implied that the author focused their research publication on improving the processing method and performance of varistors rather than replacing them with other materials as varistor-based ceramics and additives or dopants.

Furthermore, we obtained that a majority of publications on SiC, CaCuTi\textsubscript{4}O\textsubscript{12}, SnO\textsubscript{2}, and ZnO varistors came from China (Figure 9). In addition, most of the publications related to CaCuTi\textsubscript{4}O\textsubscript{12} and SnO\textsubscript{2} were published by authors from the country of Brazil after China, with Japan being the third and fourth for SiC and ZnO-based varistor applications, respectively. In Figure 10, we found that China was recorded to have the highest publications associated with Bi\textsubscript{2}O\textsubscript{3} and BaO in their research. South Korea represented the highest number of articles published related to Pr\textsubscript{6}O\textsubscript{11} and V\textsubscript{2}O\textsubscript{5} as the main additive in varistor ceramics. Japan and South Korea were also among the top 5 countries publishing articles on each varistor form. Other

**Figure 10.** Top five countries based on the number of publications of the designated varistor formers.
nations, such as Malaysia, the United Kingdom, Algeria, Taiwan, Mexico, and Spain, were listed only once in different additives.

3.7. Limitation of study

By restricting the search for “varistor” to titles and abstracts, it is possible that the search results will not cover all articles on Scopus related to varistor. This could happen because some researchers might choose other terms to express their interest in research. Also, due to missing journal information, VOSviewer may have overlooked some author keywords in the co-occurrence analysis during the database screening. Future studies are suggested to compare the outputs of different databases, such as Scopus and Web of Sciences. For example, Web of Science’s search results automatically display the most popular articles in the field, which indicates that the paper receives a lot and fast citation after publication. Using various types of data sources to conduct a bibliometric analysis will help in the exploitation of a more interesting and comprehensive study.

4. Conclusion

This study used the Scopus database to deliver a mainstream outlook on the development of varistor research between 1951 and 2021, encompassing up to 2122 articles published in standard journals and conference proceedings. During the initial data collection stage, essential procedures to exclude irrelevant review articles were performed. Then, VOSviewer software was used to create a sequence of figures that could be used to better understand the textual information. Later, following the arrangement obtained from the Scopus website, a series of tables to tabulate the data of the leading journals and authors globally were produced. The publication growth was discerned to begin at a snail pace during the first 23 years and only started to increase the rate from 1975 onwards. Although the trend was observed to become sideway after 2004, it is clear that the general trend still retains its aggressive increment, with 2020 generating the highest annual publication number. As such, it is expected that the research trends of varistor will continue to increase in the coming years as more people rely on electronic devices throughout their days. Additionally, we also discovered that countries/institutions from China, United States, South Korea, and Japan have contributed the highest number of published articles, with their accumulative value reaching more than 50% of the overall publications. These major players in the varistor research field can act as an example for other countries with fewer publications to follow while also serving as a possible international collaborator. We have presented a case study to examine the popularity of varistor-based ceramics and additives used by researchers throughout the years. We found that ZnO and Bi$_2$O$_3$ were the most popular varistor-based ceramics and additives, respectively. On the other hand, we have identified several ceramic materials that are currently well discovered such as varistor-based ceramics with their additives incorporating nanomaterials, and we have also discussed some areas newly studied with varistors, such as capacitor-varistor dual-function components, low-voltage varistor application, wet chemical fabrication method, sintering technique, degradation behavior, and stability of varistor performance, which can be potential hot topics for future studies. Lastly, the efforts to explore low-cost materials and methods, which are nontoxic and accessible, are likely to continue.

Acknowledgments

Muhamad Syaizwadi Shaifudin expressed his most profound appreciation for the doctoral scholarship sponsor, Universiti Malaysia Terengganu, Malaysia.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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