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EDITED BY
Chenye Wu,
The Chinese University of Hong Kong, Shenzhen, China

REVIEWED BY
Changhui Liu,
China University of Mining and Technology, China
Jun Yin,
North China University of Water Resources and Electric Power, China

*CORRESPONDENCE
Yubing Duan,
3135667433@qq.com

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# Development and research trends of a polypropylene material in electrical engineering: A bibliometric mapping analysis and systematical review

Yubing Duan[1]*, Yonggui Zhao[2], Guoqing Ma[1], Xiaobin Sun[3], Hao Zhang[1] and Wenbo Liu[4]

[1]State Grid Shandong Electric Power Research Institute, Jinan, China, [2]State Grid Linyi Power Supply Company, Linyi, China, [3]State Grid Shandong Electric Power Company, Jinan, China, [4]School of Electrical and Information Engineering, Changsha University of Science and Technology, Changsha, Hunan, China

In order to explore the development and research trends of polypropylene (PP) in electrical engineering, the research literature is quantitatively analyzed using a bibliometric method with the VOSviewer and CiteSpace software. First, the research literature about PP material in electrical engineering applications is collected, from 1990 to 2022. Then, by analyzing the keyword co-occurrence, keyword co-occurrence timezone, author cooperation network, and national cooperation network, the research hotspots of the PP field and its time evolutionary path and development direction are introduced. It is found that the nano-modification, mechanical, and electrical properties are the most popular research hotspots in this field. Most research studies were completed by few specific researchers. A stable cooperative group has not been formed in this field yet, indicating the necessity of further integration. Most articles about PP were published in dielectric and material journals. It is suggested that more open access journals are required to popularize the existing research results among the public and to promote the development of PP. Although the most published country is China, the United States publishes the most cited papers on average.

KEYWORDS

**polypropylene, bibliometric, visualize, research hotspots, development skeleton**

## Introduction

Polymers have a broad application prospect in electrical engineering. The development of polymers has gone through stages from natural rubber and polyvinyl chloride to synthetic rubber (butyl rubber and ethylene propylene rubber) and polyethylene to cross-linked polyethylene (XLPE) (Huang et al., 2018). However, parts of polymers such as thermoset XLPE, which is widely used in power cables, consume a lot of energy and cause environmental problems during the manufacturing

TABLE 1 Properties of iPP, sPP, and aPP[1–7].

| Material\properties | iPP | sPP | aPP |
|---|---|---|---|
| Density (g/cm$^3$) | 0.92–0.94 | 0.89–0.91 | 0.85–0.91 |
| Melting point (°C) | 165 | 135 | 130 |
| Yield point strength (Mpa) | 28 | 20 | 27 |
| Breaking point strength (Mpa) | 53 | 3 | 33 |
| Elongation (%) | 770 | 523 | 327 |
| Dielectric constant | 2.2–2.3 | 2.38 | 3 |

Here, data [1–7] are cited by Huang et al. (2018), Jin (1996), Kou (2014), Yong et al. (2021), Yoshino et al. (2003), Z. C. Zhang et al. (2015), and Zhao et al. (2022).

and recycling processes. The "double carbon" policy has put forward higher requirements of the power industry in the field of environmental protection and innovation and recycling of insulation materials (Lin et al., 2022). Compared to XLPE, the production of polypropylene (PP) does not need cross-linking processes with short production periods, which can save a great deal of energy. In addition, the recyclable properties of PP meet the demand of the "double carbon." Therefore, the development of high-performance PP is expected to be an important part to construct large capacity, long distance and green energy industry.

The molecular formula of PP is $(CH_3CH_6)_n$, with asymmetric methyl groups on the main chain. Based on the arrangement of methyl groups, three different stereoscopic structures of PP are classified. When all methyl groups are located on one side of the main chain, it is called isotactic PP (iPP). Also, the methyl groups of syndiotactic PP (sPP) are alternately located on both sides of the main chain, whereas those of atactic PP (aPP) are located irregularly on both sides (Wypych, 2013; Ouyang et al., 2022a). iPP and sPP can crystallize, while aPP is an amorphous material. Also, the higher isotacticity indicated the stronger crystallization ability. The common properties of different PPs are listed in Table 1. Specifically, both iPP and sPP have multiple forms of crystal, in which the most common form are $\alpha$, $\beta$, and $\gamma$ (Varga, 1989; Lotz, 1998). Their melting point, density, and mechanical properties differ from those of the crystalline form. Apart from the crystalline type, it is reported that the size distribution of spherulite also plays an important role in affecting the properties of PP (S. Chen et al., 2016; Sun et al., 2000; Wang et al., 2011).

The practical application of PP is constrained by multiple factors such as its heat resistance, mechanical, and anti-aging properties. To meet the requirement of different industrial operations, the properties of PP need to be improved by modification (Hu et al., 2022b), for example, for use in power cables as an insulating medium; the properties of insulation resistivity, heat resistance, and water resistance should be emphasized (H. Chen et al., 2022). For use in power capacitors, PP is usually desired to have a higher dielectric constant while maintaining a higher insulation strength and lower losses (Bonart et al., 2020). Fang et al. (2013) improved the impact resistance and fatigue resistance of PP by treating it with long glass-fiber reinforcement so that it can be used in the wind turbine blades.

When applying PP to the field of electrical engineering, both thermology and mechanology, dielectric physics, high-voltage insulation, and other multidisciplinary should be considered. The study only from the perspective of a single discipline may not be sufficient to fully understand the real operating mechanism of PP in electrical engineering. Particularly for new researchers, it is often difficult to find the frontier and development direction in this field from the intertwined research. Therefore, this paper used the bibliometrics method and analyzed the research hotspots and the time evolution path of PP application in the electrical engineering field. The purpose of this paper is to solve the following questions:

1) What are the keywords studied by PP in electrical engineering? What is the relationship between these keywords?
2) What are the keyword timezone and the outbreak words? What is the responding path of time evolution in this field?
3) Who are the main authors who have studied PP in the electrical engineering field? What is their relationship?
4) Which are the most published journals in the field? Which country contributes the most?

# Materials and methods

## Research methods

The conception of bibliometrics can be traced back to the beginning of the 20th century. By using mathematics and statistics, bibliometrics can quantitatively analyze the latest progress and research frontier in one field (Merigo et al., 2015; Ma and Xi, 2022). Using bibliometric software, knowledge maps can be constructed to reveal the internal relations between objects through citation analysis. Typical bibliometric mapping software includes Bibexcel, CiteSpace, VOSviewer, SciMAT, and HistCite. VOSviewer and CiteSpace are the most popular mapping software in bibliometrics (Pan et al., 2018). VOSviewer can construct the relationship map of keywords, research institutions, authors, etc., which has the excellent characteristics of simple drawing (Waltman, 2010). CiteSpace uses the set theory to study the similarity in knowledge units. Based on the similarity algorithm, the timezone and timeline view in the time slice can be outlined to clear the evolution path and development direction in the field (G. M. Chen, 2009). This paper used aforementioned two software to draw the knowledge map. The keyword timezone map was drawn by CiteSpace to answer the second question in the introduction. Also, the rest of the questions analyzed the keywords, authors, and journals using VOSviewer. Despite the fact that drawing software was used, it can clearly show the

TABLE 2 Data sources and selection methods.

| Data source | Web of Science |
|---|---|
| Index | SCI-EXPANDED and SSCI |
| Search strategy | TS= ["polypropylene" and ("insulation" or "breakdown" or "electric" or "conduction" or "dielectric" or "cable" or "capacitor" or "high voltage" or "electrical properties")] |
| Researching period | From 1990 to 2022 |
| Search cut-off time | 22 July 2022 |
| Literature type | Article and review |
| Language | English |
| Sample size | 3,565 literature records |

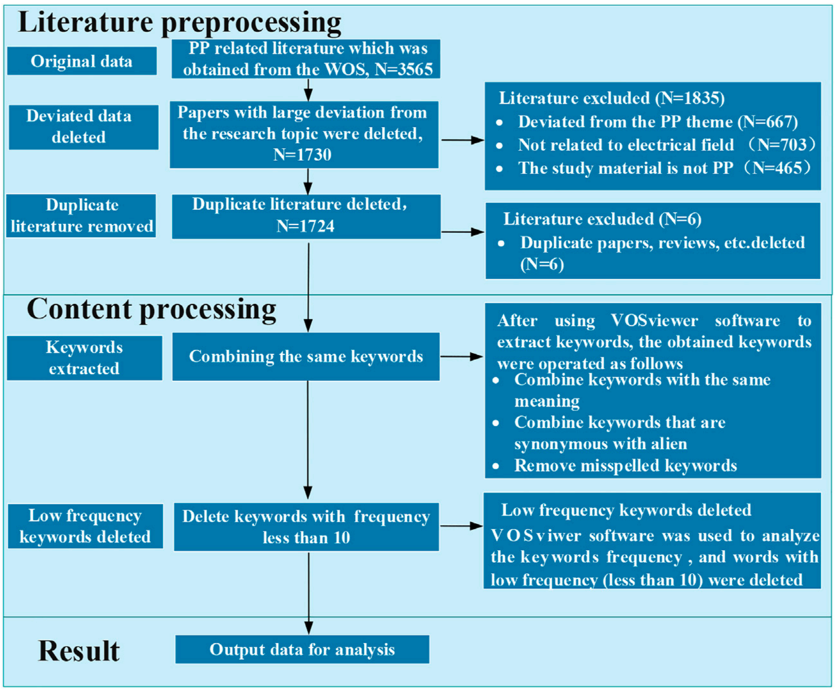


FIGURE 1
Process of data cleaning.

development trend in this field, and it is still hard to get to know the core and in-depth development in the field. Therefore, this paper also provides literature reviews to quantitative analyze the development trends.

## Data source

The Web of Science (WOS) database is selected as the data source. The reason to choose such database is because WOS is one of the most widely used high-quality literature resource databases with the most complete information by scholars from all professions and trades. On the other hand, it is also considered the ideal database for bibliometric analysis (Ding and Yang, 2020). SCI-EXPANDED and SSCI are selected as citation indexes. To ensure that the samples basically contain all PP applications in electrical engineering, the search strategy was TS = ["polypropylene" AND ("insulation" OR "breakdown" OR "electric" OR "conduction" OR "dielectric" OR "cable" OR "capacitor" OR "high voltage" OR "electrical properties")]. Also, the researching period is from 1990 to 2022. The search cut-off time was 22 July 2022. Both Article and Review are selected. Also, language is selected as English. The initial screening results showed that a total of

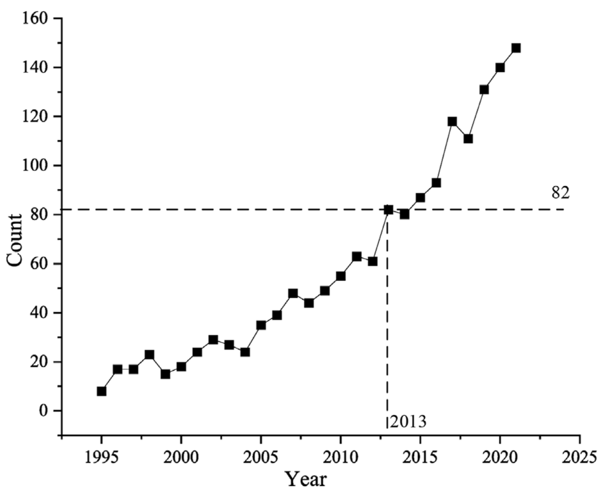


FIGURE 2
Number of literature studies from 1995 to 2021.

3,565 records (3,464 articles and 101 review papers) are selected. The data sources and selection methods are summarized in Table 2.

## Data cleaning

The initial data obtained from WOS are relatively rough as the resulting sample contains duplicates, deviations from the topic, synonyms, and other problems, which are called dirty data. The conclusions drawn from dirty data would not be credible (Stramer, 2015). Therefore, the data are cleaned of duplicate documents, documents with large deviations from the topic, synonymous entries, and low-frequency keywords. The specific steps are shown in Figure 1.

## Literature description

After data cleaning, 1,724 literatures, which come from a total of 5,800 authors in 1,439 research institutions across 74 countries, remained. They are published in 412 journals. Also, a total of 38,387 references are cited from 7,023 journals.

Figure 2 shows the number of studies published in the time slice from 1995 to 2021. The number of papers showed an upward tendency with years. It is low until 2013 and then increased significantly. From 2013 to 2021, the publication number of papers stabilized at more than 85 per year, indicating that PP is receiving gradually increasing attention from researchers in the field of electrical engineering.

# Results and discussion

## Co-occurrence on keywords

Keywords are a summary to show the core research essence of the article. By analyzing the co-occurrence of keywords, the hotspots and trends of research studies in the field could be studied. Considering that analyzing all the keywords is a laborious and insignificant task, only keywords with high frequency are selected for analysis. Donohue et al. (Betty, 1974) proposed that the demarcation between the high- and low-frequency keywords can be calculated using the following equation:

$$T = \frac{-1 + \sqrt{8I_1 + 1}}{2}, \tag{1}$$

where $I_1$ is the number of keywords with a frequency of 1 in the samples.

By analyzing the cleaned 1,724 articles, the number of keywords with a frequency of 1 is 51. Substituting the number 51 into Eq. 1, $T = 9.6$. Therefore, the threshold value of high-frequency keywords is chosen to be 10. Also, the remaining keywords are used for co-occurrence analysis, as shown in Figure 3.

Every node represents a keyword in Figure 3. Also, the size of the node represents the frequency of the keywords. The connecting lines between nodes represent the association strength. A thicker line means a greater frequency of the two keywords appearing in the same literature. Nodes with the same color belonged to a cluster representing the same type of research topic. In order to clarify the relationship of keywords, the keywords whose frequency is more than 120 times are listed in Table 3.

The three largest nodes in Figure 3 are “polypropylene,” “nano-composites,” and “composites,” among which the keyword “nano-composites” provides a clue for the research hotspot in the field of PP. Although PP has an acceptable performance with the advantage of retrievability, its thermal, electrical, and mechanical properties still restrict its practical applications. Therefore, it is necessary to improve parts of the characteristics of PP to meet the requirement of industrial applications. There are three main modification ways for PP: 1) copolymerization/blend, 2) nano-doping, and 3) grafting (Hu et al., 2022b). Nano-doping modification is the hottest research topic for PP materials in electrical engineering. Research studies show that the doping nanoparticles into PP could modify one or parts of the special properties of the matrix polymer, such as high permittivity (Z. Li et al., 2018), low dielectric loss (Womble et al., 2018), corona-resistance (Hajiyeva et al., 2016), high and low temperature-resistance (Zhou et al., 2019), high breakdown strength (Zhou et al., 2015), and electrical tree-resistance (Hu et al., 2022a). The modification effects depend on the type, size, shape, and concentration of nanoparticles. The interface between

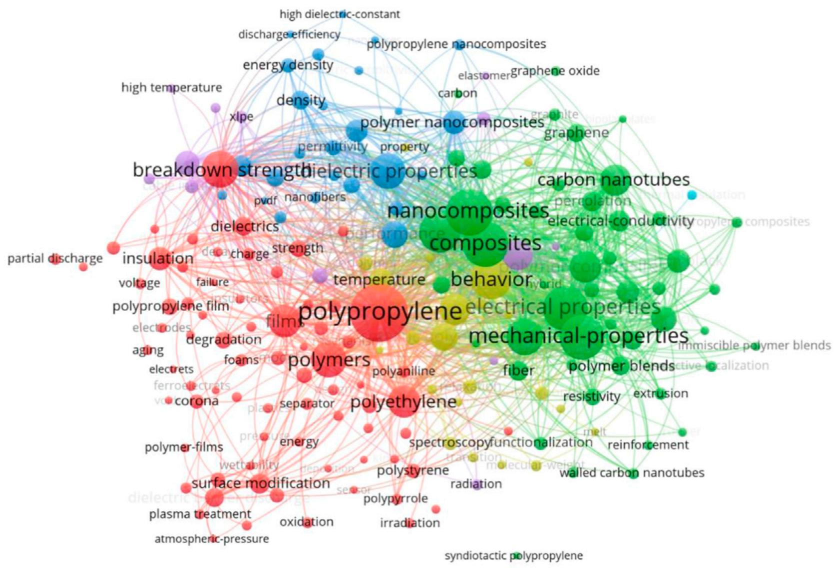


FIGURE 3
Co-occurrence keywords.

TABLE 3 Main keywords.

| Keyword | Occurrence | Total link strength | Keyword | Occurrence | Total link strength |
|---|---|---|---|---|---|
| Polypropylene | 441 | 2,237 | Polymers | 166 | 777 |
| Nano-composites | 286 | 1767 | Dielectric properties | 165 | 937 |
| Composites | 279 | 1,558 | Polyethylene | 137 | 786 |
| Mechanical properties | 263 | 1,580 | Films | 134 | 712 |
| Electrical properties | 261 | 1,606 | Carbon nanotubes | 132 | 877 |
| Behavior | 223 | 1,242 | Crystallization | 129 | 827 |
| Conductivity | 218 | 1,226 | Polymer composites | 125 | 804 |
| Morphology | 178 | 1,201 | Blends | 120 | 722 |
| Breakdown strength | 174 | 926 | | | |

nanoparticles and polymer is widely accepted. However, the effects of nano-modification technology heavily rely on the homogeneous dispersion of nanoparticles which plays a vital role in nano-modification. Therefore, the influence of nanoparticle dispersion on the modification effect is very important. Esthappan and Joseph (2014) pointed out that an appropriate amount of nanoparticles can effectively improve the insulation of PP. However, more nanoparticles could cause agglomeration, and then reduce the insulating properties. Umemori et al. (2012) show that with the mass fraction of $SiO_2$ nanoparticles at 2.3%, the nano-modified PP shows the best tensile strength. Dispersing nanoparticles homogenously should be the focus of future research studies. Surface modification of nanoparticles is one of the effective measures to improve the dispersibility. Research studies show that when treating PP with different surface modifiers such as titanate coupling agent NDZ-201 (Ji et al., 2005) and maleic anhydride (Lee et al., 2010), the mechanical properties are improved to different degrees. From the previous analysis, the preparation process, modification method, and forming mechanism of crystal are important research directions to further enhance the performance strength of PP.

Further exploration of the co-occurrence keywords map shows that electrical properties, conductivity, and breakdown strength are secondary keywords in this research field. Among them, the conductivity and breakdown strength are two of the

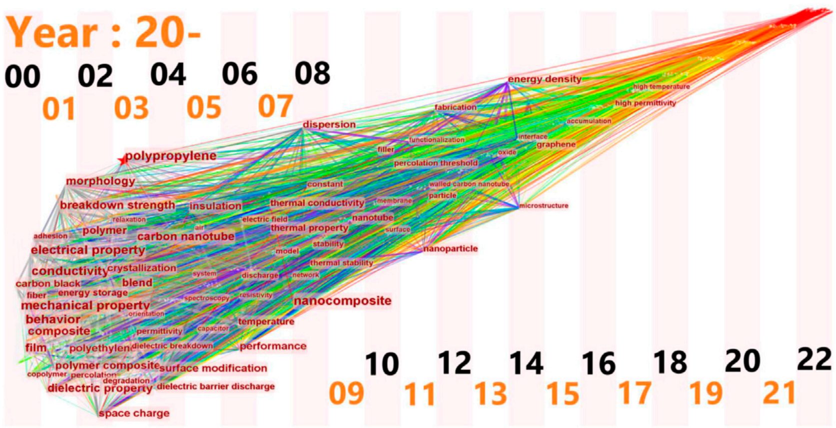


FIGURE 4
Map of timezone.

most important parameters when studying the electrical properties of PP. The breakdown strength determines the maximum electric field strength that the insulating material can withstand. The breakdown strength of PP is about 123% times higher than that of XLPE when the temperature reaches the maximum operating temperature of XLPE (90°C) (Ouyang et al., 2022b). Therefore, PP is believed to be more suitable as insulation material for high-voltage power equipment. The superior electrical properties of PP are attributed to the supramolecular structure (Diao et al., 2017). Compared to the crystalline, the amorphous region, especially the poloidal junction, is less resistant to high-energy electrons. As a result, these regions are usually believed to be the weak points for breakdown. Krishnakumar et al. (2010) postulated that the degree of crystallinity would affect the breakdown strength when the amorphous regions constitute a small part of the whole volume. Also, the production processes, including chemical modification, blending, and nano-doping modification, change the supramolecular structure of PP, affecting the electrical properties (Sun et al., 2019; Bonart et al., 2020; Qi et al., 2020). Moreover, when subjected to mechanical stresses, the spherical crystals inside PP would be deformed. It may introduce defects at the interface of spherical crystals, which decreases the breakdown strength of PP. Conductivity is an important parameter of insulating materials. On the one hand, the conductivity affects the dielectric loss in the application. On the other hand, for DC power equipment, such as DC cables, the temperature-dependent conductivity of PP directly affects the DC electric field distribution (Huang et al., 2020). As there is a temperature gradient inside the insulation and it varies with the operating loads, the temperature-dependent conductivity of the insulation materials makes the electric field distribution of DC cables more complex than that of AC cables (S. X. Zhang et al., 2022). Therefore, as a potential insulation material for future cables, it is necessary to gain insight into the temperature-dependent conductivity properties of PP to master the operating characteristics of PP-based DC cables.

## Timezone and burst words

In order to understand the developing progress of PP in electrical engineering, the timezone of keywords is analyzed by CiteSpace. The selected time span is from 2000 to 2022, and the time slice length is 1. The keyword threshold is chosen as 8. Due to the different calculation methods of CiteSpace and VOSviewer, the keyword frequency may be slightly different. The threshold is appropriately reduced to ensure that the core keywords are not missed. The results of the keywords' timezone are shown in Figure 4. The color of the nodes represents the number of citations of the keyword in different years. The connecting lines between the nodes represent the co-occurrence of two keywords, and the connecting lines with the same color represent a cluster.

The research of PP in the electrical engineering field can be roughly divided into three periods. The first period is from 2000 to 2004. The research mainly focused on studying the basic properties, including the mechanical, electrical, and dielectric performance, of PP. The research themes in the second period from 2005 to 2011 included two aspects. One is the research on thermal properties, covering thermal conductivity, thermal property, thermal stability, etc. The other aspect is about the modification techniques of PP. The nanoparticles, including nanotube and graphene, constituted the one type of main keywords for this time period. The third period is from 2012 to the present. The application of PP in the practical power industry gradually received much attention. The research studies do not only focus on the functional properties of PP, but

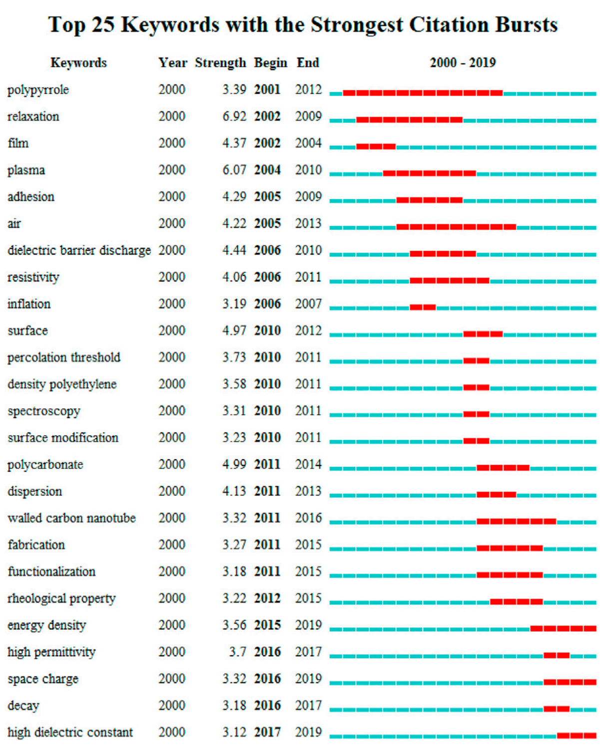


FIGURE 5
Burst words in PP filed during the past 20 years.

also on the development of new insulating materials with high dielectric and temperature resistance. From the perspective of a time evolution path, the research on PP has gradually changed from theoretical mechanisms to engineering applications.

Burst words are the frequent occurrence of keywords in the field during a period of time. The study of burst words can not only show the evolution of research hotspots over time, but also help understand the research trends in recent years. In order to clarify the sudden outbreak of research hotspots in the field of PP application in electrical engineering, this paper uses CiteSpace to analyze the burst words during the past 20 years. The results are summarized in Figure 5.

By analyzing the burst words shown in Figure 5, the years of the burst words are distributed between 2001 and 2019. The burst words of relaxation phenomena, dielectric barrier discharge, resistivity, and inflation indicated that the PP was only used in special applications as an insulator. Due to the rapid development of measurement technology, the study of PP has gradually shifted to sub-micro and microscopic areas. The surface properties, percolation phenomena, and the dielectric spectroscopy emerged as the burst words. In addition, people began to pay attention to the relationship between PP's own microstructure and macroscopic properties. They tried to adjust the physicochemical properties of PP from density modification, surface modification, and nano-modification. Starting from 2012, it is realized that PP can be used as insulation material for power equipment such as power cables and capacitors. Typical representative burst words are energy density, high permittivity, and high dielectric constant, which represent the important application prospects in the field of capacitors. Also, the burst words of space charge and decay are related to the problem of accumulation and dissipation of space charges in DC high-voltage cables on the insulation.

Moreover, the intensity of the burst words are all greater than three, indicating that PP in electrical engineering has been a popular area for researchers. From the distribution year, the burst words have been continuing to bring forth the new through the old. The last time of burst word is 2019, which is closer to the present. It could be strongly believed that PP will bring new innovations in the field of electrical engineering in the next few years.

## Collaborative network

The collaborative network between authors can reveal the core authors and institutions in the field. The literature studies analyzed in this paper comprise 5,800 authors. However, most of them only published one article in this field, and the total number of this kind of article is 3,000. The most productive author published 43 articles to promote PP application in electrical engineering. According to Price's law (Price, 1963), an author who publishes articles can be regarded as the author in the field. The threshold number for the core author can be calculated by Eq. 2.

$$\boldsymbol{m} = \mathbf{0.749} \times \sqrt{\boldsymbol{n}_{\boldsymbol{max}}}, \tag{2}$$

where $n_{max}$ is the publication number of the most productive author, $n_{max} = 43$. Therefore, $m = 4.91$. The authors with more than five articles can be regarded as the core authors. Core authors with more than 12 articles are listed in Table 4.

The core authors are visually mapped for collaborative network using VOSviewer, as shown in Figure 6. The node size represents their publication number, and the line between the nodes represents the existence of collaborative relationships. The gradation of color from blue to yellow represents the active periods of authors. In addition, the cluster analysis of core authors provides insight into the collaborative relationships between the research communities in the field, as shown in Figure 7.

The author with the most publications in this field is Boxue Du, with a total of 43 publications and 335 citations which has an average of eight citations per article. The research of Boxue Du involves conductivity characteristics (Ran et al., 2018), space charge characteristics (J. Li et al., 2022), and nano-modification technologies for PP application in cable insulation (Du et al., 2021). From Figure 7, the core authors in the PP electrical engineering field can be divided into eight clusters, which are the main impetus for this field to move forward.

TABLE 4 Distribution of core authors.

| Author | Document | Citation | Total link strength | Author | Document | Citation | Total link strength |
|---|---|---|---|---|---|---|---|
| Boxue Du | 43 | 335 | 79 | Xiao, Meng | 17 | 34 | 48 |
| Dang, Zhi-Min | 28 | 897 | 40 | Li, Qi | 16 | 608 | 58 |
| Ramazanov, M. A. | 25 | 133 | 30 | Li, Zhonglei | 16 | 128 | 34 |
| Dascalescu, Lucian | 22 | 154 | 23 | Hajiyeva, F. V. | 15 | 105 | 26 |
| He, Jinliang | 22 | 659 | 67 | Huang, Xingyi | 13 | 645 | 21 |
| Li, Shengtao | 21 | 379 | 34 | Jiang, Pingkai | 13 | 645 | 21 |
| Zhou, Yao | 21 | 706 | 71 | Liu, Chuntai | 13 | 390 | 48 |
| Hu, Jun | 20 | 658 | 67 | Cho, Jeon-Wook | 13 | 115 | 30 |
| Zha, Jun-Wei | 19 | 660 | 45 | | | | |

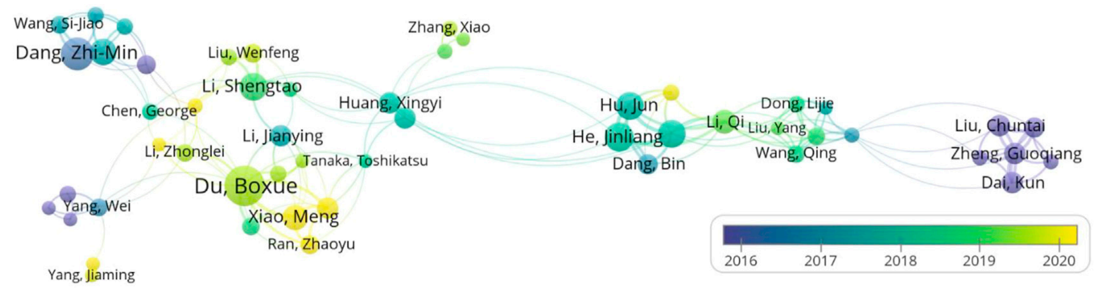


FIGURE 6
Author collaboration network.

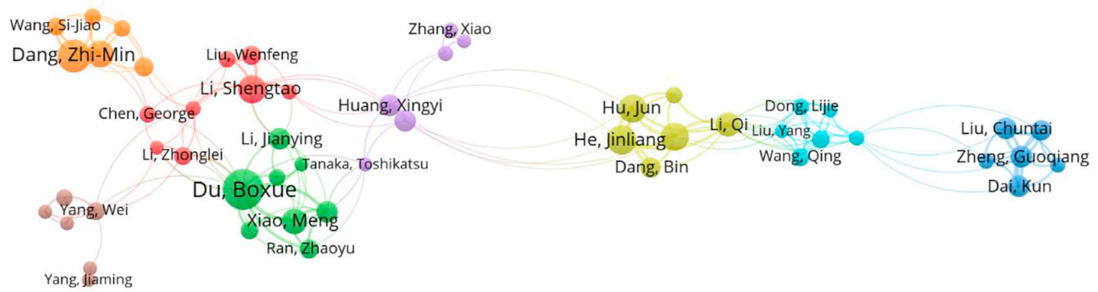


FIGURE 7
Clustering analysis of core authors.

Price's law (Price, 1963) is introduced to assess whether the field has formed a stable collaborative group. If half of the papers are contributed by a group of highly productive authors and the number of papers from this group is equal to or higher than the square root of the number of articles, the authors are considered to have formed a stable collaboration group in the field. The calculation formula is as follows:

$$\sum_{m+1}^{s} n(x) = \sqrt{N}, \tag{3}$$

where $s$ is the maximum number of papers in the field, $m$ is the threshold number for defining the core author, $n(x)$ is the number of authors who have written $x$ papers, and $N$ is the total number of authors.

TABLE 5 Main journals in PP application in electrical engineering.

| Rank | Source | Document | Citation | Total link strength |
|---|---|---|---|---|
| 1 | IEEE Transactions on Dielectrics and Electrical Insulation | 145 | 3,234 | 331 |
| 2 | Journal of Applied Polymer Science | 108 | 2,167 | 147 |
| 3 | Composites Science and Technology | 54 | 2,865 | 128 |
| 4 | IEEE Transactions on Applied Superconductivity | 43 | 307 | 27 |
| 5 | Polymer Composites | 36 | 416 | 67 |
| 6 | Polymer | 35 | 1,337 | 83 |
| 7 | Polymers | 27 | 282 | 44 |
| 8 | Acs Applied Materials and Interfaces | 22 | 1,562 | 51 |
| 9 | Journal of Physics D: Applied Physics | 22 | 1,083 | 81 |
| 10 | IEEE Transactions on Plasma Science | 21 | 649 | 78 |
| 11 | Journal of Electrostatics | 21 | 237 | 32 |
| 12 | Journal of Materials Science | 21 | 769 | 41 |
| 13 | Macromolecules | 20 | 1,017 | 49 |
| 14 | Polymer Engineering and Science | 20 | 251 | 39 |

There are 152 core authors in the total of 5,800 authors. Also, the most productive author has published 43 articles. A total of 1,299 articles were published individually. Using Eq. 3, it is found that the result did not meet the requirements of Price's law. Meanwhile, the number of core author is 37. Their publications accounts for the only 22.4% of all publications in this field, which also does not meet the requirement of Price's law. Therefore, it can be considered that the field PP application in electrical engineering has not formed a stable cooperative group yet.

## Journals and countries

In order to find the main journals in this topic, 412 journals of the articles in this study are analyzed. Among these, 14 journals have published more than 20 relevant papers, as listed in Table 5.

As can be seen, most of the articles are published from dielectric or material journals, among which "IEEE Transactions on Dielectrics and Electrical Insulation," "Journal of Applied Polymer Science," and "Composites Science and Technology" published 145, 108, and 54 articles separately. It is worth noting that among the top 20 journals, only "polymers" is an open access journal, indicating that there is a need to further popularize the research results for free to the public. Also, "IEEE Transactions on Dielectrics and Electrical Insulation" (TDEI) is the most cited journal. This journal mainly focuses on dielectric phenomena; research and development of vacuum, gaseous, liquid, and solid dielectrics; and electrical insulating components of systems. The articles about PP published in TDEI reaches 3,234, with an average of 22 citations per article, indicating the high quality and the frontier position in the field.

Country analysis can further reflect the urgency of each country to develop this research field. These literature studies

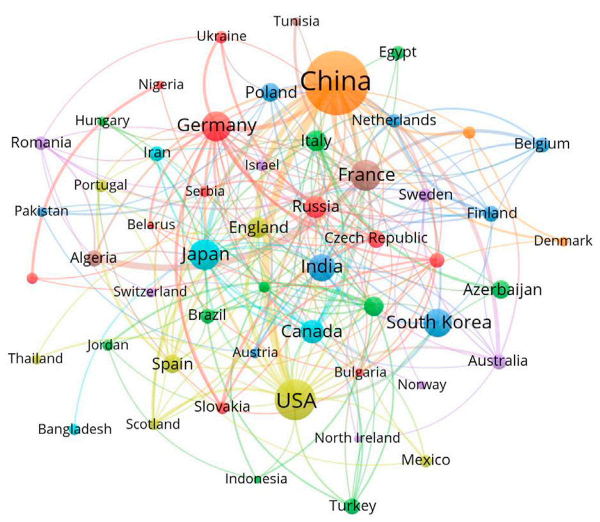


FIGURE 8
Countries' cooperation network.

came from a total of 74 countries, and the cooperation network between countries is shown in Figure 8. Larger nodes indicated higher number of articles from the respective country. The same color of nodes means the countries belong to the same cluster. Also, the connecting line between the nodes represents the association strength between countries. The countries with top 10 numbers of publications are shown in Table 6.

China is the most productive country in this field. It has published 582 articles with 13,531 citations, which accounts for 33.76% of the total number of papers. Therefore, China is

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TABLE 6 Top 10 countries in terms of the number of articles published in PP.

| Country | Document | Citation | Total link strength | Average citation |
|---|---|---|---|---|
| China | 582 | 13,531 | 2,127 | 23 |
| USA | 198 | 14,559 | 1,073 | 74 |
| Japan | 104 | 2044 | 314 | 20 |
| France | 103 | 2,796 | 526 | 27 |
| Germany | 96 | 3,935 | 573 | 41 |
| South Korea | 93 | 2,195 | 292 | 24 |
| India | 81 | 2,781 | 205 | 34 |
| Canada | 60 | 4,116 | 403 | 69 |
| Russia | 51 | 1,033 | 146 | 20 |
| England | 47 | 937 | 363 | 20 |

considered to be the most promising country to promote the application of PP in the field of electrical engineering. This is due to the strong demand for long-distance transmission caused by the imbalance in the distribution of energy and consumption in China (Shi et al., 2022). Moreover, China's rapid economic development and urbanization in recent years has led to a higher demand for power quality and high-voltage cables than that in other countries. Therefore, there is an urgent need to develop new environmentally friendly PP insulation materials in China. It is also noticed that USA is the second most published country in the field, with a total of 198 articles and 14,559 citations. Also, Japan is the third with 104 articles and 2,044 citations. Both of these countries are developed countries in terms of the electricity industry. However, the average citation rate for papers published in the United States is 73.53, which is much higher than that of China (23.25 per article). In addition, it is worth noting that cooperation among countries appears to be increasingly frequent. Countries, such as USA, Spain, and England, have similar research topics such as cable ampacity improvement (Leee, 1984), aging mechanism (Grabmann et al., 2018), and thermal performance (Salavagione. et al., 2016). This is due to the earlier construction of power systems in Europe and the United States, resulting in their mature power grid facilities. One of the only remaining important ways to further improve the operational stability of power systems is to enhance the basic material properties. In addition, China is the country that cooperates most closely with other countries. Compared to other countries, the connecting line between China and the United States, which is one of the most academically developed countries, is the strongest. This is perhaps due to the open academic climate in China. It is believed that continued cooperation between the China and the United States would rapidly promote the large-scale application of PP to electrical engineering.

## Conclusion and prospects

As an environmentally friendly insulation material, PP is of great significance for the long-term development of the electric power engineering. Also, the development of high-performance PP insulation materials will be an iterative and updated research topic. In this paper, the research related to the application of PP in electrical engineering, in recent 30 years, was analyzed.

(1) The application of PP in electrical engineering has gone through three main stages: the basic physical properties, the performance modification, and the industrial application. The thermal stability, thermal conductivity of PP, and its electrical conductivity and space charge properties are of major interest to research scholars. Also, nano-technology is currently one of the most published ways for modification.
(2) In total, 152 core authors are working on the development of environmentally friendly PP applications in the power industry. Among them, Boxue Du is the most productive author in this field around the world. The core authors can be roughly divided into eight groups. However, the researchers have not formed a stable collaborative group yet.
(3) The top three journals are "IEEE Transactions on Dielectrics and Electrical Insulation," "Journal of Applied Polymer Science," and "Composites Science and Technology." The field needs to further popularize the existing scientific research results to the public for free.
(4) With 33.76% of the total number of papers published, China is the most active country in this field. However, the international impact of papers published in the US is much higher, with an average citation count of 74.

Combining the evaluation results, the development direction and future trends of PP in electrical engineering can be predicted as follows:

(1) The application of PP in electrical engineering is an iteration and renewal proceedings. In the future, this field will form a new discipline covering materials, science, mechanics, high-voltage insulation technology, and other interdisciplinary disciplines. Polypropylene, a new type of insulation material, is expected to replace traditional energy-intensive insulation materials, contributing to the realization of the "Dual Carbon."
(2) The field has gradually evolved from a theoretical discipline to an engineering application discipline. Future research studies would focus on the utilization of modification, nano-doping, and other ways to enhance the properties of PP for application in practice.
(3) Although there is still academic divergence on the best way to achieve access to papers, the idea that scientific research results should be freely available to the public has been widely accepted. The proportion of open access journals will continue to expand to promote the development in the future.

This paper has the following limitations due to some objective factors. First, the data resources were only selected from SCI-EXPANDED and SSCI in WOS without considering other databases (e.g., Scopus). Second, the quantitative analysis of the data in the text is limited by the authors' knowledge of developments in the field. Based on the previous analysis, the following points need to be addressed in future studies:

(1) In the process of studying the physicochemical properties of PP, it is recommended that the relationship between microscopic molecular and macroscopic properties be established from the microscopic molecular structure to guide the targeted development of high-performance materials.
(2) Scholars and research groups should strengthen the communication between different disciplines and countries. It is recommended that individual scholars strengthen their academic exchange by attending more international conferences or as visiting scholars. When forming a research team, it is recommended that scholars from different disciplines join the team.
(3) Readers can take care of journals such as "IEEE Transactions on Dielectrics and Electrical Insulation," "Journal of Applied Polymer Science," and "Composites Science and Technology" to keep up to date with developments in the field to a certain extent.

## Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

## Author contributions

YD contributed to the conception of the study; YD, YZ, GM, and WL contributed significantly to analysis and manuscript preparation; YD, GM, and HZ performed the data analyses and wrote the manuscript; and HZ and YD helped perform the analysis with constructive discussions.

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## Conflict of interest

Author YZ was employed by the company State Grid Linyi Power Supply Company, and author XS was employed by the company State Grid Shandong Electric Power Company.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note



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