Review

The Bibliometric Analysis and Review of the Application of Plasma in the Field of VOCs

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Abstract: The application of plasma in the field of volatile organic compounds (VOCs) can be traced back to the 1990s and has gradually developed into an important research field. In this regard, this article primarily sorts and analyzes the literature on the “application of plasma in the field of VOCs” in the Web of Science core collection database from 1992 to 2021 and, subsequently, obtains important data and trends, including the annual number of articles published, country, institution analysis, and journal, as well as discipline analysis, etc. The results show that China is not only in a leading position in the field of research, but also has six top-ten research institutions. This field has more research results in engineering, chemistry, physics, and environmental disciplines. In addition, this article summarizes dielectric barrier discharge (DBD) and titanium-containing catalysts, which represent the discharge characteristics and type of catalyst highlighted through the hot keywords. This review will provide certain guidance for future, related research.

Keywords: plasma; bibliometric; titanium-containing catalyst; dielectric barrier discharge

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1. Introduction

As a common air pollutant, volatile organic compounds (VOCs) are widely derived from the processing and production processes of various industries, such as the exhaust emissions in the production process of petrochemical products, waste incineration flue gas emissions, and processing gas emissions from steel coking production. As a series of harmful pollutants, they (VOCs) include alkanes, alkenes, alcohols, ketones, aldehydes, aliphatic hydrocarbons, aromatic hydrocarbons, chlorinated organic pollutants, sulfurized organic pollutants, and nitrogenous organic pollutants, etc. [1], which are very harmful to the ecological environment. Commonly, VOCs will consume ozone in the atmosphere, destroy the ozone layer, and cause phenomena such as photochemical smog and urban haze. In addition, VOCs are harmful to the ecological environment and cause great harm to human health. Long-term exposure of the human body to certain VOCs will cause various incurable and irreversible diseases, such as cancer, various respiratory diseases, skin diseases, and so on [2]. In the context of the era of large VOCs emissions, from 1970 to the present, the world has held many conferences, concluding, as well as promulgating, extensive, related agreements, laws, and regulations, including the “Clean Air Act” promulgated by the United States in 1970, which required 70% of pollutant emission reductions to be achieved by 2000; the “Gothenburg Protocol”, which required member states to reduce

emissions of pollutants by half of that in 2000 by 2020 [3]; the “Stockholm Convention”, which entered into force in 2004 and also aims to strengthen the management of chemicals and reduce the harm caused by chemicals, especially toxic and hazardous chemicals [4]. Therefore, the problems caused by controlling and reducing VOCs emissions have become the responsibility of all countries in the world.

The research on plasma dates back to 1705 when Francis Hauksbee was charged and discharged under vacuum for the first time [5]. This was the beginning of plasma research. In the 1830s, Faraday and others began to study the phenomenon of gas discharge. In 1857, Siemens and others studied the generation of ozone from atmospheric oxygen discharge [6]. By 1879, Crooks and others in the United Kingdom used a fourth state other than liquid, solid, or gas to describe the ionized gas in the gas discharge vessel [7]. In 1928, American scientists Irving Langmuir and Tonks introduced the term “plasma” into physics for the first time to describe the form of matter in a gas discharge tube. As a result, plasma emerged in the form of a physics term. Plasma is an ionized gas which is composed of some generated positive and negative ions after the electrons have been deprived of atoms and the ionization of atomic groups. The movement of macroscopically neutral ionized gas with a scale larger than the Debye length is mainly dominated by electromagnetic force and exhibits significant collective behavior. Plasma can decompose gas into various, high-speed, charged particles, including electrons, molecules, atoms, active radical groups, etc. It can also excite the gas to generate metastable and excited molecules, atoms, and active radical groups [8,9]. Distinguished by the reaction temperature, plasma is divided into high-temperature plasma (thermal plasma) and low-temperature plasma (non-thermal plasma or cold plasma); the apparent reaction temperature of the former can reach 20,000 °C or even higher, and it has the advantages of high temperature, high intensity, high energy density, and non-ionizing radiation. The apparent reaction temperature of the latter only reaches room temperature or slightly higher than room temperature. Its advantages are low apparent temperature, high electron energy, low energy consumption, and high efficiency. The application of plasma in the field of VOCs mainly includes VOC degradation, by-product control and resource utilization [10,11], high-sensitivity detection [12,13], etc. In related research, the number of reports on the degradation of VOCs is the largest, and it is also the most popular based on the international environment. For a long time, scholars in many countries have been working on the degradation technology of VOCs. VOC degradation technologies include the adsorption method, condensation method, membrane separation method, biochemical method, direct combustion method, catalytic combustion method, plasma oxidation, and plasma catalysis [14–22], etc. Plasma technology has been widely favored by scholars from various countries in recent years due to its high efficiency, high cost performance, and low energy consumption, which indicates that low-temperature plasma technology is a promising technology.

The statistical method based on bibliometrics has a wide range of applications in many disciplines and fields. The purpose of this research is to analyze and organize the data obtained using bibliometric statistical methods, including a comprehensive analysis of the number of articles, author country, author institution, journal subject distribution, author keywords, etc. This article analyzes, organizes, and summarizes the article data on the “application of plasma in the field of VOCs” in the Web of Science core collection database from 1992 to 2021 (the term first appeared in this field in 1992) and summarizes the hot content of “application of plasma in the field of VOCs”.

2. Data Sources and Methodology

The statistical data of the article were mainly derived from the Science Citation Index Expanded (SCI-EXPANDED) citation index of the Web of Science core collection database. The data collection date was 28 June 2021, and the subject heading was composed of two parts: A and B, in which A represents the expression forms of plasma in the literature, including: “plasma”, while B stands for volatile organic compounds in different expressions in the literature, including “VOCs” or “VOC” or “Volatile Organic Compounds” or “Volatile

Organic Compound”. The article makes a statistical analysis of all relevant document types, countries, affiliated institutions, keywords, authors, and subject classifications in the core database of Web of Science from 1901 to 2021. In this measurement analysis, Microsoft Office 2016, Origin 2021, ESRI ArcGIS 10.2, etc., were used for data processing, retrieval, analysis, and drawing [23–27].

3. Results and Discussion

According to the bibliometric analysis data, in the Science Citation Index Expanded (SCI-EXPANDED) citation index of the Web of Science core collection database, a total of 1501 articles about “application of plasma in the field of VOCs” from 1 January 1992 [28] to 28 June 2021 were included. This article only systematically analyzes 1181 academic papers from 1997 to 2021 (nearly twenty-five years) in terms of the number and trends of articles, country and institution analysis, journal and discipline analysis, and hot keywords. At the same time, several typical keywords with high frequency are systematically reviewed.

3.1. Number of Articles and Trend Analysis

Generally speaking, the number of articles in a field is an important indicator to evaluate the development trend, current situation, and prospects of related fields. Figure 1a shows the number of academic articles on “application of plasma in the field of VOCs” from 1992 to 2021; Figure 1b shows the total number of publications of “plasma applications in the field of VOCs” from 1992 to 2021. It can be seen from Figure 1 that the related literature on “application of plasma in the field of VOCs” began to appear in 1992. However, in the seven years from 1992 to 1998, the number of articles in this field was relatively small, indicating that the development of this field was relatively slow and had a lack of creative breakthroughs in the first few years. Since 1999, the number of academic articles increased significantly, nearly twice that of the first few years; this may be attributed to the plasma technology which began to make breakthroughs in 1999. It is worth mentioning that the number of articles in this field reached the maximum in 2020 (117 articles), which may be due to the decrease in people’s daily activities during the new coronavirus epidemic in 2020 and researchers devoting more time to scientific research. The red, dotted line in Figure 1 shows the trend of academic articles and total publication volume of “application of plasma in the field of VOCs” from 1992 to 2021; it can be seen that, although the academic articles and the total publication volume of plasma applications in the field of VOCs show volatility, the overall trend is increasing. Additionally, the upward trend is more obvious since 1999, which shows that the field of “application of plasma in the field of VOCs” is in the rising period of research, and it is also a current research hotspot. Scholars are becoming more and more interested in this field.

Figure 1. The number of academic articles on the application of plasma in the field of VOCs (a) and the total number of publications (b) from 1992 to 2021.

3.2. National and Institutional Contributions

Generally, data analysis of countries/regions is capable of determining which countries/regions have higher influence and the best research foundation in this field. Among them, academic articles from mainland China, Hong Kong, Macau, and Taiwan are all classified as “China”; academic articles from England, Scotland, Northern Ireland, and Wales are all classified as “United Kingdom”. After re-categorizing, among the 1181 academic papers in the past fifteen years, 69 countries were involved, the number of papers published in a single country/region was 1004, accounting for 85.01%, and the number of papers published in cooperating countries/regions was 177, accounting for 14.99%. Table 1 shows the top 10 productive countries from 1997 to 2021; it can be seen that China’s number of posts in this field ranks first, with 424 posts, accounting for 29.8%; the United States is in second place, with 145 articles, accounting for 10.2%; France is in third place, with 111 articles, accounting for 7.8%; and Japan and South Korea are in fourth and fifth places, with 93 and 85 articles. Although both the United States and France have posted more than 100 articles, there is a big difference in the number of articles issued compared with China. The total number of articles issued by China in this field is almost equal to the total number of articles issued by the United States, France, Japan, and South Korea.

Table 1. Top 10 productive countries from 1997 to 2021.

Rank	Country	TP	TP R (%)
1	China	424	29.8%
2	USA	145	10.2%
3	France	111	7.8%
4	Japan	93	6.5%
5	South Korea	85	6.0%
6	Germany	67	4.7%
7	UK	47	3.3%
8	Italy	38	2.7%
9	Poland	35	2.5%
10	Belgium	33	2.3%

Note: TP is the number of total publications; TP R (%) is the ratio of the number of one journal’s publications to the total number of publications.

In order to vividly show the contributions of countries and continents in the field, ESRI ArcGIS 10.2 geographic information system software was used to sort out the number of articles issued by various countries, and the results are shown in Figure 2. Figure 2 presents the distribution of the number of articles published by various countries in the world from 1997 to 2021. The different shades of color in the picture represent the number of articles issued by different countries in this field. The darker the color, the more articles published. In the figure, it can be clearly seen that the articles in this field are mainly concentrated in China, the United States, and France. At the same time, Japan, South Korea, Germany, and other countries are also prominent in this field. In addition, countries in Europe and North America have extensive research in this field; Africa, South America, and Asia have relatively poor participation in research in this field, and only China has a large proportion of them.

Generally speaking, the data analysis of different research institutions can well show the research level in this field. Through analysis, in the fifteen years from 1997 to 2021, a total of 1036 institutions published 1181 academic papers. Table 2 shows the data analysis of the top 10 institutions in terms of publication volume. Among the top ten institutions, there are six institutions distributed in China and one each in Japan, Belgium, the United Kingdom, and France. This illustrates China’s leading position in this field. Zhejiang University ranked first, with 49 articles, accounting for 4.1%; Dalian University of Technology ranked second, with 40 articles published, accounting for 3.4%; third place is the Japanese organization National Institute Advanced Industrial Science and Technology, with 22 articles (1.9%); the Chinese Academy Sciences of China and Ghent University of Belgium

ranked fourth and fifth, with 22 articles (1.9%) and 17 articles (1.4%), respectively; the organizations ranked sixth to tenth issued fewer articles, but the number of articles published was relatively average, with the number of each being around 15. Zhejiang University, which ranks number one, has a wide range of research content in this field, including plasma combined with catalysis and synergistic degradation of conventional VOCs [29,30] and malodorous gases [31], as well as the recycling of pollutants [10] and the control of harmful by-products [11]. Some scholars also carried out related simulation work [32]. Dalian University of Technology, ranked second, mainly studied the degradation of VOCs by low-temperature plasma synergistic catalysts in this field [33–36]; the National Institute Advanced Industrial Science and Technology and Chinese Academy Sciences, ranked third and fourth, have done a lot of work on the plasma catalytic degradation of VOCs, as well as high-sensitivity VOC gas sensors [12,13,37,38].

Figure 2. Geographical distribution of articles, 1997–2021.

Table 2. Top 10 productive institutions from 1997 to 2021.

Rank	Institution	TI	TI R (%)	SI R (%)	CI R (%)	FI R (%)	RI R (%)
1	Zhejiang University, China	49	1 (4.1)	1 (5.1)	4 (2.1)	1 (3.9)	1 (3.8)
2	Dalian University of Technology, China	40	2 (3.4)	2 (3.1)	1 (4.0)	2 (2.6)	2 (2.6)
3	National Institute Advanced Industrial Science and Technology, Japan	22	3 (1.9)	3 (1.9)	6 (1.8)	3 (1.5)	3 (1.5)
4	Chinese Academy Sciences, China	22	3 (1.9)	5 (1.2)	2 (3.2)	5 (1.3)	4 (1.4)
5	Ghent University, Belgium	17	5 (1.4)	5 (1.2)	6 (1.8)	6 (1.1)	7 (1.0)
6	University of Manchester, UK	16	6 (1.4)	5 (1.2)	11 (1.6)	6 (1.1)	7 (1.0)
7	Shanghai Jiao Tong University, China	16	6 (1.4)	4 (1.7)	87 (0.5)	4 (1.4)	4 (1.4)
8	University Paris 11, France	14	8 (1.2)	5 (1.2)	27 (1.1)	10 (0.9)	12 (0.8)
9	Sichuan University, China	14	8 (1.2)	11 (1.1)	15 (1.3)	8 (1.0)	6 (1.1)
10	South China University of Technology, China	14	8 (1.2)	5 (1.2)	27 (1.1)	8 (1.0)	7 (1.0)

Note: TI is the number of total publications in a certain institution; TI R (%) is the ratio of the number of one institution's publications to the total number of publications; SI R (%) is the ratio of the number of one single institution's publications to the total number of all single institutions' publications; CI R (%) is the ratio of the number of one cooperate institution's publications to the total number of all cooperate institutions' publications; FI R (%) is the ratio of the number of one institution's publications to the total number of all institutions' publications (the institution is where the first author is located); RI R (%) is the ratio of the number of one institution's publications to the total number of all institutions' publications (the institution is where the correspondence author is located).

3.3. Journal and Subject Distribution

Through the analysis and sorting of 1181 academic papers in this field searched in the Web of Science, it was also easy to obtain key information about different journals in this field. Table 3 shows the top ten journals in terms of publication volume during the

fifteen years from 1997 to 2021. These include total publications, the ratio of one journal's publications to the total publications, total citations, citations per publication, impact factor in 2021, and H-index. The journal with the most publications in this field is PLASMA CHEMISTRY AND PLASMA PROCESSING, with 77 publications, accounting for 6.5%. The second-ranked journal is CHEMICAL ENGINEERING JOURNAL, with 62 articles (5.2%). The journals ranked third and fourth are JOURNAL OF HAZARDOUS MATERIALS and APPLIED CATALYSIS B-ENVIRONMENTAL, with a volume of approximately 40 articles each; 44 (3.7%) and 42 (3.6%), respectively. The fifth and sixth journals are JOURNAL OF PHYSICS D-APPLIED PHYSICS and IEEE TRANSACTIONS ON PLASMA SCIENCE, with 34 (2.9%) and 26 (2.2%) publications, respectively. The remaining journals have published fewer than 20 articles. Among the top ten journals in terms of publication volume, three academic journals have an impact factor of more than 10, six journals have an H-index of more than 100, and four journals have an H-index of more than 200. APPLIED CATALYSIS B-ENVIRONMENTAL has the highest impact factor (19.503), while ENVIRONMENTAL SCIENCE & TECHNOLOGY has the highest H-index (345). From the above data analysis, it can be seen that articles in this field are usually published in some high-impact journals, which also reflects that the research in this field, at this stage, is relatively hot and innovative.

Table 3. Top 10 productive journals from 1997 to 2021.

Rank	Journal	TP	TP R (%)	TC	CCP	IF	H-Index
1	PLASMA CHEMISTRY AND PLASMA PROCESSING	77	6.5	1844	23.9	3.148	57
2	CHEMICAL ENGINEERING JOURNAL	62	5.2	1938	31.3	13.273	172
3	JOURNAL OF HAZARDOUS MATERIALS	44	3.7	1415	32.2	10.588	235
4	APPLIED CATALYSIS B-ENVIRONMENTAL	42	3.6	294	70.1	19.503	205
5	JOURNAL OF PHYSICS D-APPLIED PHYSICS	34	2.9	583	17.1	3.207	172
6	IEEE TRANSACTIONS ON PLASMA SCIENCE	26	2.2	715	27.5	1.222	98
7	CHEMOSPHERE	19	1.6	522	27.5	7.086	212
8	PLASMA SCIENCE & TECHNOLOGY	18	1.5	98	5.4	1.567	27
9	ENVIRONMENTAL SCIENCE & TECHNOLOGY	16	1.4	620	38.8	9.028	345
10	JOURNAL OF ELECTROSTATICS	15	1.3	374	24.9	1.775	70

Note: TP, number of total publications; TP R (%), ratio of the number of one journal's publications to the total number of publications; TC, number of total citations; CCP, citations per publication; IF, impact factor in 2021; H-index refers to his or her having, at most, h papers cited at least h times.

Table 4 shows the focus and proportion of subjects in this field in the past fifteen years. It is clear to see that the subject that has participated the most is engineering, with 441 articles published, accounting for 23.41%. The second- and third-ranked disciplines are chemistry and physics, with 359 (19.06%) and 281 (14.92%) posts, respectively. The fourth place is environmental science and ecology, with 219 articles published, accounting for 11.62. The number of articles in the fields in fifth to tenth places is less than 100, and the proportion is relatively small. It can be seen that, in this field, the main focus is in the research of engineering, chemistry, physics, and environmental disciplines, while the disciplines of materials science mainly play a supporting role.

Table 4. Top 10 productive territories from 1997 to 2021.

Rank	Territory	TP	TP R (%)
1	Engineering	441	23.41%
2	Chemistry	359	19.06%
3	Physics	281	14.92%
4	Environmental Sciences and Ecology	219	11.62%
5	Materials Science	81	4.30%
6	Biochemistry and Molecular Biology	64	3.40%
7	Science and Technology—Other Topics	64	3.40%
8	Spectroscopy	38	2.02%
9	Instruments and Instrumentation	28	1.49%
10	Energy and Fuels	27	1.43%

Note: TP is the number of total publications; TP R (%) is the ratio of the number of one subject's publications to the total number of publications.

Figure 3 shows the trend chart of the number of articles issued by the top five disciplines in the past five years. It can be seen from the figure that all disciplines are on an upward trend as a whole, but individual disciplines have fluctuated in the volume of publications each year. For example, although the number of papers issued by engineering disciplines is the largest, the number of papers issued during 2017–2018 is less than that of chemistry disciplines, and the number of papers issued by engineering disciplines in 2020 is less than that in 2019. This may be because the arrival of the 2020 epidemic has affected the development of the engineering field, resulting in a decrease in the number of publications. Similarly, the number of articles in the field of engineering also decreased from 2016 to 2017. The possible reason is that the world economic crisis in 2016 affected the development of the field of engineering, so the number of articles in the field of engineering in 2017 and 2018 was relatively small. At the same time, the corresponding increase in the number of articles published in the field of environmental science and ecology can also support this conclusion; among the top five disciplines, only the two disciplines of physics and environmental science and ecology have maintained an upward trend in publishing articles, while the number of publications in this field in materials science has always been ranked last. It shows that this field is more a combination of basic science and practical application and has the characteristics of a multi-disciplinary intersection.

Figure 3. The annual number of each top 5 productive subjects during 2016–2020.

3.4. Keyword Analysis

For an article, author keywords often represent the theme and main idea of the article. At the same time, they also reflect the corresponding research fields and research directions. Author keywords can be analyzed from two aspects: on the one hand, they can be analyzed from the frequency of occurrence, which reflects the research enthusiasm of keywords in

this field. On the other hand, they can be analyzed from the relationship between keywords; this reflects the relevance and intersection of the two keyword research fields. It can be said that keyword research reflects the research direction and research hotspots of a field. Based on the statistics of keywords, in the 1181 academic articles from 1997 to 2021, a total of 2645 keywords appeared with a total frequency of 4812. Among them, we merged the keywords of different expressions of “VOCs” (“vocs”, “volatile organic compounds”, “volatile organic compound”, “voc”) into “volatile organic compounds”, combined the keywords of different expressions of “NTP” (“non-thermal plasmas”, “nonthermal plasma”, “non thermal plasma”, “non-equilibrium plasma”, “low-temperature plasma”) into “non-thermal plasma”, and merged the keywords of different expressions of “DBD” (“dielectric barrier discharge plasma”, “dielectric barrier discharge (dbd)”, “dbd plasma”) into “dielectric barrier discharge”. Thus, the 20 keywords with the highest frequency in Table 5 were obtained. It can be seen from Table 5, excluding the two keywords used in our literature search, “volatile organic compounds” and “plasma”, that keywords with a high frequency included “non-thermal plasma”, “dielectric barrier discharge”, “toluene”, “ozone”, “catalyst”, “TiO₂”, etc. The above information shows that the dielectric barrier discharge low-temperature plasma catalytic degradation of VOCs has the most research interest in this field.

Table 5. The 20 most frequent keywords from 1997 to 2021.

Author Keyword	97–21 TP	97–21 R (%)	Author Keyword	97–21 TP	97–21 R (%)
volatile organic compounds	251	1 (26.5)	TiO ₂	24	11 (2.5)
non-thermal plasma	208	2 (22)	photo catalysis	23	12 (2.4)
dielectric barrier discharge	127	3 (13.5)	oxidation	22	13 (2.3)
toluene	89	4 (9.4)	adsorption	22	13 (2.3)
plasma	75	5 (7.9)	corona discharge	19	15 (2)
ozone	49	6 (5.2)	catalytic oxidation	19	15 (2)
catalyst	42	7 (4.4)	voc removal	18	17 (1.9)
plasma catalysis	36	8 (3.8)	decomposition	17	18 (1.8)
catalysis	35	9 (3.7)	trichloroethylene	16	19 (1.7)
benzene	28	10 (3)	synergetic effect	13	20 (1.4)

Note: TP: Total numbers of publications. R (%): Rank (the percentage of articles in total publications is given within brackets).

According to the relevance of the author’s keywords in the same article and different articles, VOSviewer was used to merge and organize the author’s keywords. In order to facilitate the display, “volatile organic compounds”, “non-thermal plasma”, and “dielectric barrier discharge” were replaced with “VOCS”, “ntp”, and “dbd”, respectively, to reduce the mutual occlusion in the picture caused by the long vocabulary. From this, the author keyword cluster map from 1997 to 2021 shown in Figure 4 was obtained. It can be seen that the keywords that are most closely related to the two search keywords include DBD, NTP, plasma-catalysis, ozone, TiO₂, etc. Among them, the representative plasma type is NTP; DBD is the most closely related to the discharge form. The keywords that represent the type of catalyst and appear the most are related to titanium-containing catalysts, such as TiO₂; this can also prove, from another aspect, that the dielectric barrier discharge non-thermal plasma catalytic degradation of VOCs has the highest research interest in this field.

Figure 5. Plate and coaxial cylindrical DBD reactors. (a) plate DBD reactor; (b) coaxial cylindrical DBD reactor.

4.1.2. Effect of Reactor

Many factors affect the form and intensity of the dielectric barrier discharge plasma discharge, including electrode material, discharge gap and length, medium material, etc. Among them, the difference in the structure of the reactor can directly affect the DBD plasma discharge form, thereby affecting the discharge intensity and discharge efficiency of the DBD plasma.

A suitable electrode material not only meets the discharge requirements of DBD non-thermal plasma to the greatest extent, but also meets the lowest energy consumption. DBD plasma has a wide variety of electrode materials, such as stainless steel [41], copper [42], nickel [43], metal oxides [44], etc. The electrode structure is mostly plate, rod, coil, and other structures. For example, Jahanmiri et al. [45] used rod electrodes made of aluminum, copper, stainless steel, iron, and brass as high-voltage electrodes and aluminum foil as ground electrodes for performance research. Results show that the electrode materials are significantly different in energy consumption, where $\text{Fe} > \text{brass} \sim \text{Cu} > \text{Al} \sim \text{steel}$. In addition, if stainless steel is used instead of copper as a high-voltage electrode, energy efficiency can be improved by 123%. Li et al. [46] studied the degradation of toluene in the DBD plasma system with different electrode structures, the results show that, under the same dual-dielectric material conditions, the rod-shaped, high-voltage electrode is better than the coil electrode in the degradation efficiency of toluene. The possible reason is that the degradation process of toluene is mainly carried out in the inner tube. The rod electrode can strengthen the electric field intensity of the inner tube, while the coil electrode shows better performance with the increase of the electric field intensity of the outer tube. However, in the study of Jiang et al. [47], the degradation efficiency of benzene with coil electrodes, rod electrodes, and bolt electrodes in a dielectric barrier/packed-bed discharge plasma reactor was compared. The degradation efficiency of the coil electrode to benzene was significantly better than that of the high-voltage electrodes of the other two structures. The reason is that the coil electrode reduces the dielectric loss of the insulating dielectric layer during the reaction, which is beneficial to the enhancement of the DBD reaction on the dielectric surface. Therefore, different electrode materials and different electrode structures have their own advantages in different reaction systems, and it is impossible to use a single standard to measure which electrode material and structure is the best choice.

Different discharge gaps usually have two sides. On the one hand, increasing the discharge gap can increase the residence time of the target gas in the reaction zone, thereby enhancing the effect. On the other hand, the increase of the discharge gap reduces the intensity of the electric field in a disguised form, resulting in a decrease in the treatment effect of the target gas. Li et al. [19] summarized the research and presented that the discharge gap of DBD plasma is generally between 1 and 15 mm. Mustafa et al. [48] compared the conversion efficiency of methane under the same DBD plasma catalytic system with a discharge gap of 3 mm and 6 mm, respectively. The results show that, when the power and discharge gap are controlled at 65.8 W and 6 mm, the average conversion

rate of methane can reach 56%. In addition, when the discharge gap is 3 mm under the same condition, the average conversion rate of methane can reach 76%. Namita Ojah et al. [49] studied the effect of the discharge gap on the surface treatment of the material under the conditions of 6 mm and 10 mm; under the condition of 6 mm, the results of surface treatment of nanomaterials are better than the surface mechanical strength and surface wettability of materials with a discharge gap of 10 mm and untreated materials. In addition, the surface cell adhesion and value-added ability of the material processed under the condition of 6 mm discharge gap is significantly higher than that of the unprocessed material. Jin et al. [50] used a trapezoidal structure reactor as a basis and, at the same time, studied the discharge in DBD plasma with a distance of 1–7 mm. When the pulse frequency was 500 Hz and the discharge gap was less than 5 mm, the discharge area presented a uniform layer discharge, and the discharges were all diffuse; when the pulse frequency was 1 kHz, the discharge in the discharge space presented irregular filamentary discharge, and the uniform discharge layer disappeared synchronously. Jiang et al. [51] increased the electrode spacing of the reactor from 20 mm to 40 mm, which reduced the degradation efficiency of toluene; increasing the electrode gap can increase the residence time of the pollutant gas, but it reduces the average electric field strength and specific input energy (SIE, which is a good indication of the energy delivered to the reactor) in a disguised form. In other words, in the DBD plasma system, the residence time of pollutant gases in the system plays a secondary role in the degradation of pollutants, while the average electric field strength and SIE play a leading role. Therefore, in order to achieve the maximum working efficiency of DBD plasma, it is necessary to weigh the pros and cons between the electric field strength and the residence time and to find the best experimental parameters through continuous experimental optimization.

Generally speaking, discharge length also has a certain influence on discharge efficiency. On the one hand, the length of the discharge affects the residence time of the pollutant gas in the system, as well as the number of micro-discharges, and the increase of the residence time and micro-discharges can increase the contact and collision of active species and electrons with target pollutants [52]. On the other hand, under the same input power condition, the increase of the discharge length reduces the power density [53]. Lee et al. [54] studied the effect of segmented electrode structure on toluene degradation under the DBD plasma catalytic system. Figure 6 shows that, at the same total discharge length, the discharge length was divided into one segment, two segments, and four segments. After the introduction of the segmented discharge structure, the current law of DBD plasma is reflected as follows: $I_{\text{four-stage}} > I_{\text{two-stage}} > I_{\text{one-stage}}$; when the electric field intensity remains unchanged, due to the increase in current, the SIE increases simultaneously, which, ultimately, leads to an increase in the degradation rate of toluene, the mineralization rate, and CO_2 . Jiang et al. [51] demonstrated the degradation of toluene with different discharge lengths in a continuous-flow sliding dielectric barrier discharge (SLDBD) reactor. Under the given U_{pulse} condition, as the discharge length continued to increase, the electric field intensity in the system also continued to increase. The reason is that the increase of the discharge length leads to the longer residence time of the pollutants in the system and the increase of the continuous discharge energy, thereby increasing the degradation performance and energy performance of the SLDBD plasma system. Guo et al. [55] compared the degradation of ethyl acetate by the double dielectric barrier discharge (DDBD) reaction system when the discharge length was 12.5 mm, 25 mm, and 50 mm. When the discharge length increased from 12.5 mm to 50 mm, the degradation rate of ethyl acetate continued to increase, reaching a maximum of 80.8%. At the same time, with the increase of the discharge length, the residence time of ethyl acetate in the DDBD reactor also increased from 0.12 s to 0.48 s, which also explains the increase in the degradation rate of ethyl acetate under the condition of increasing discharge length. However, Wang et al. [53] studied the conversion of methane by the dielectric barrier discharge micro-plasma and found that, at a constant input power, the increase of the discharge length reduces the power density of the reaction zone, resulting in a decrease in the conversion rate of the target

gas. In addition, the heat dissipation of the dielectric layer in the reaction also increases with the increase of the discharge length, resulting in more energy loss. Therefore, in the research, the discharge length suitable for the experimental requirements can be considered according to the focus of different experiments, so as to maximize the utilization effect of the DBD plasma reaction system.

Figure 6. One-stage, two-stage, four-stage electrode discharge structure diagram.

Dielectric material affects the discharge intensity and micro-discharge due to the difference in dielectric constant. The difference in the dielectric constant of different dielectric materials leads to the difference in dielectric capacitance; the dielectric capacitance and the air gap capacitance are connected in series in the circuit. Increasing the dielectric capacitance increases the electric field strength of the discharge gap, resulting in more micro-discharges [19]. Common dielectric materials include glass [56–58], quartz [59], plexiglas [33], alumina [60], ceramics [61], and polytef [51]. Quartz dielectric materials have been widely used in research and commercialization due to the characteristics of heat resistance, high strength, and high cost performance [62]. In the research, it was found that, in addition to quartz dielectric, other dielectric materials were also studied by scholars because of some special properties. Wang et al. [63] found that, in the DBD plasma system, the dielectric material changes the electric field strength in the discharge gap by changing the equivalent dielectric capacitance. Li et al. [64] studied the auxiliary discharge behavior of two dielectric materials of zirconia ($\epsilon = 25$) and polytetrafluoroethylene ($\epsilon = 25$) in a DBD packed-bed reactor. The effects of two dielectric materials on the production of active particles in the DBD plasma catalytic system and their kinetics were described. Four types of discharge process, including high-voltage side streamer discharge and ground side dielectric surface discharge, were produced. Moreover, the discharge generation mechanism of two nitrogen-active species and one oxygen-active species was revealed, and research confirmed that PTFE dielectric materials have better active species excitation performance than zirconia dielectric materials. Kundu et al. [65] studied the difference in the discharge properties of quartz and alumina dielectric materials in the DBD plasma system. The results show that, although the electric field strength in the reactor with alumina medium is lower than that in the reactor with quartz medium, the dielectric constant of alumina medium is greater than that of quartz medium. The dielectric capacity and micro-discharge density in the discharge gap are higher than that of the quartz medium, so the installation of the alumina medium reactor can obtain a higher methane conversion rate. Similarly, Khoja et al. [66] explored the CO_2 conversion rate of methane by comparing quartz dielectric materials and alumina dielectric materials. The results show that, under the same conditions, the maximum conversion rates of methane and CO_2 of alumina are 74% and 68%, respectively, while the CO/H_2 ratio and energy efficiency are higher than those of quartz dielectric materials. This is because the porous and fluffy nature of alumina increases the residence time of the gas in the discharge area, resulting in more particles colliding with the target gas molecules, thereby increasing the large conversion efficiency.

That porous materials increase the adsorption of target gas molecules and residence time in the discharge area has also been confirmed in previous studies [57,67].

4.1.3. Summary

Among the factors that affect the degradation of VOCs in the DBD plasma system, the structural factor of DBD has a decisive impact. The main reason is that factors, such as electrode material, discharge gap and length, and medium material, change the equivalent capacitance of the discharge area to varying degrees and so achieve the effect of changing the discharge form and discharge intensity in order to improve the degradation efficiency and mineralization rate of VOCs by the DBD plasma system, etc. In fact, there are relatively few studies on DBD reactors, mainly due to the relative lack of research on the discharge behavior and the complexity of gas discharges by researchers [9]. In addition, compared with an effective, packed catalyst, simply changing the reactor structure has a limited effect on the overall system performance. The filling of the catalyst not only changes the degradation efficiency of VOCs, but also has many advantages in the degradation of harmful by-products, degradation of O_3 , improvement of mineralization rate, and carbon balance. Titanium-containing catalysts not only have greater advantages in the catalytic degradation of VOCs but are also widely favored by researchers due to their special photoelectric properties. Therefore, the research on coupling titanium-containing catalysts in the research of DBD plasma system is also a development trend.

4.2. DBD Plasma Synergizes with Titanium-Containing Catalysts to Degrade VOCs

In order to study the degradation of VOCs by DBD low-temperature plasma with titanium-containing catalysts, it is necessary to identify target pollutants and classify the specific role of different titanium-containing catalysts in DBD plasma to determine the corresponding catalyst types and forms required for the degradation of different pollutants.

4.2.1. Target Pollutants

In the process of discharging various industrial pollutants, there are hundreds of different types of VOC, and the efficient and harmless degradation of VOCs is still a major difficulty in environmental governance. Table 6 summarizes the basic situation of different target pollutants in various studies of DBD and titanium-containing catalysts in the past ten years. According to the different chemical structures of these target pollutants, we divided them into several categories: aromatics, ketones, aldehydes, alcohols, alkanes, alkenes, and halocarbons. In the DBD and titanium-containing catalyst catalytic system, the research on aromatics (such as toluene, benzene, styrene, etc.) is the most frequent among the research on conventional VOCs. Chen et al. [68] studied the degradation efficiency and mineralization rate of toluene in the catalytic system of DBD and a $TiO_2/Al_2O_3-Co_3O_4/AC$ (Ti-Co) catalyst. When the relative humidity was 30%, the specific input energy was $65 J \cdot L^{-1}$, and the pollutants in the DBD discharge area passed through a 10 cm TiO_2/Al_2O_3 catalyst-packed column and a 20 cm Co_3O_4/AC (Ti-Co) catalyst-packed column, respectively; the degradation efficiency of toluene and the selectivity of carbon dioxide reached 72% and 44%, respectively. Liu et al. [69] researched the degradation of toluene and the selectivity of carbon dioxide under the synergistic catalytic system of DBD and $TiO_2-C/5A$. The results show that, when the DBD discharge area is filled with $TiO_2-C/5A$ catalyst, the toluene degradation efficiency and carbon dioxide selectivity reach 99.6% and 83%, respectively, which is much higher than the 79.5% and 37.5% achieved when filled with no catalyst. This is because the doping of carbon facilitates the generation of photoelectron holes, reduces the energy band gap, and facilitates the growth of more active species on the surface of the catalyst. In addition to the research on aromatics, scholars have also studied the degradation of other types of VOC in the catalytic systems of DBD and titanium-containing catalysts. Zeng et al. [70] used DBD plasma to explore the influencing factors and mechanism of Cu-doped MnO_2 catalysts to degrade acetone and methyl ethyl ketone. In the degradation process of acetone and methyl ethyl ketone, the degradation efficiency

of methyl ethyl ketone was always higher than that of acetone, and the maximum value could reach 97%. The reason is that the doping of Cu accelerates the generation of surface active substances, thereby accelerating the efficiency of the reaction. At the same time, the doping of Cu can also optimize the utilization of ozone and the complete oxidation of VOCs. Ghaida et al. [71] found that the simultaneous application of NTP and UV is favorable for the cleavage of butyl groups on VOCs, and the addition of TiO₂ promotes the degradation of butyraldehyde, reduces the release of ozone, and improves the mineralization rate and CO₂ selectivity. Sivachandiran et al. [72] investigated the relative humidity of the air on the adsorption and regeneration of isopropanol on the TiO₂ catalyst. The humidity slowed the adsorption of isopropanol on the catalyst surface but played a positive role in increasing the mineralization rate and reducing by-products. Zhang et al. [73] compared traditional TiO₂ and TiO₂-coated γ -Al₂O₃ catalysts prepared by sol-gel method in synergistically removing styrene from DBD. Among them, nano-TiO₂-coated catalysts had more catalytic oxidation activity than traditional catalysts. Simultaneously, compared with traditional catalysts, the catalyst prepared by the sol-gel method had an increase in the degradation rate of ozone of 18%, and the phenomenon of carbon deposition was also significantly reduced.

Table 6. Overview of various VOCs degraded by DBD and titanium-containing catalysts.

Classification	VOCs	Reference
Aromatics	Toluene	[68,69,74–81]
	Styrene	[82–84]
	Benzene	[85,86]
	Xylene	[87]
	Phenol	[35]
	Naphthalene	[83,88]
Ketones	Acetone	[70,89]
	Methyl ethyl ketone	[70]
	Butane-2,3-dione and Heptan-2-one	[90]
Aldehydes	Formaldehyde	[91]
	Acetaldehyde	[92]
	Butyraldehyde	[71]
Alcohols	Isopropanol	[72,89]
Alkanes	Butane	[93,94]
Alkenes	Ethylene	[73,94]
Halocarbons	Chlorobenzene	[95]
	Chloroform	[96]

In addition, most of the research on VOCs was carried out around the C–H–O composition type of VOC, and we cannot ignore that there is a class of VOC containing halogen elements, such as chlorobenzene, chloroform, etc. The toxicity for this type of VOC is usually relatively large, and the impact on the environment and humans is also more serious. Song et al. [95] studied the degradation of chlorobenzene in a DBD catalytic system using CoMn/TiO₂ and CeMn/TiO₂ catalysts. The results show that, when NTP was present, the catalytic activity of the CoMn/TiO₂ catalyst was significantly better than that of CeMn/TiO₂; the degradation efficiency of chlorobenzene reached 97.1% and a carbon dioxide selectivity of 65.5% on a calculated carbon balance of 99.1%, respectively. However, under thermo-catalytic conditions, the effects of the two catalysts were completely opposite. According to the relevant by-products and characterization analysis, it was finally concluded that NTP plays a leading role in the degradation of chlorobenzene, and the catalyst plays a major role in reducing the formation of harmful by-products.

4.2.2. Titanium-Containing Catalysts

Normally, the titanium-containing catalysts filled in DBD low-temperature plasma include ferroelectrics-type catalysts [81,97–99] (e.g., BaTiO₃, etc.), semiconductor [78,83,86,95,100–107] (TiO₂)-supported catalysts, and titanium-supported catalysts [108–113] (e.g., TiO₂/5A, TiO₂/ γ -Al₂O₃, etc.). The most common type is the titanium-supported catalyst, which

mainly improves the electric field strength and micro-discharge through the good dielectric properties of titanium dioxide, which increase the degradation efficiency of pollutants. The support of titanium can also enhance the formation of surface active groups on the catalyst, thereby increasing the mineralization rate and suppressing the formation of harmful by-products. Gandhi et al. [93] used a TiO₂-loaded glass wool (GW) catalyst to explore the degradation performance of butane in a DBD catalytic system. Although there is no difference in the degradation of butane between GW loaded with TiO₂ and pure GW, GW loaded with TiO₂ shows good catalytic performance in terms of mineralization rate and CO₂ selectivity. Tang et al. [35] compared the phenol degradation rate of granular activated carbon (GAC) and TiO₂-GAC hybrid materials in the DBD plasma catalytic system. The TiO₂-GAC hybrid material had better phenol degradation efficiency than the GAC material in a DBD plasma system; the highest degradation efficiency reached 88%, and it also had better performance in catalyst activation and regeneration. This is actually due to the increased active species, such as hydroxyl groups, on the GAC surface, caused by the addition of titanium. Zhu et al. [114] studied the degradation of toluene by a titanium-doped composite catalyst, and the results showed that the toluene degradation efficiency of the titanium-doped, double-nucleated catalyst can reach 99% under an energy efficiency of 2.1 g/kWh. Gandhi et al. [94] compared the TiO₂- and ZrO₂-coated γ -Al₂O₃ filling materials under the DBD NTP system at 150 °C and studied the degradation of butane and ethylene. The degradation efficiency of TiO₂-coated γ -Al₂O₃ was higher than that of γ -Al₂O₃ alone, but it produced a large amount of formaldehyde, acetaldehyde, and other harmful by-products. The ZrO₂-coated γ -Al₂O₃ showed good performance in reducing harmful by-products and increasing the mineralization rate. Zhu et al. [115] studied the effect of an F-TiO₂/ γ -Al₂O₃ composite catalyst on the degradation of toluene. The experimental results show that the filling of F-TiO₂/ γ -Al₂O₃ catalyst can reach a high degradation rate of toluene (>99%). The reason is that the doping of F-TiO₂ increases the porosity and pore structure of the catalyst, so that the catalyst has a better adsorption performance for toluene, thereby increasing the degradation efficiency of toluene. The research on semiconductor (TiO₂)-supported catalysts is mainly the combination of electro-catalysis and photocatalysis. TiO₂ has better photocatalytic performance; photocatalysis is actually the photocatalytic oxidation process (PCO), which occurs when electrons on the surface of the catalyst receive energy greater than that required for electron transitions and provide strong oxidative properties through the generated electron holes (Figure 7) [116]. The key reactions related to photocatalytic oxidation are as follows (Table 7): firstly, the TiO₂ catalyst generates electron holes and free electrons by absorbing light energy, and then the free electrons generate O₂^{•−} and H₂O by hitting O₂ and H₂O. Finally, under the action of PCO, VOCs react with O₂^{•−} and OH[•] to form the final products CO₂ and H₂O [116,117]. For TiO₂, it can utilize the energy generated by many kinds of light sources (including the light energy generated by plasma discharge) because TiO₂ has a wide band gap. In addition, its higher dielectric constant can improve the electrocatalytic performance of TiO₂ in a packed bed. During the discharge of DBD plasma, in addition to the inherent electrical properties of micro-discharge, it also exhibits some of the light properties caused by the discharge. Therefore, the combination of a TiO₂-supported catalyst and DBD can amplify the advantages of both and achieve the greatest photoelectric catalytic effect. Barakat et al. [89] studied the oxidation performance of isopropanol (IPA) and acetone on the surface of a TiO₂-packed bed in a DBD plasma reactor. In the study, it was found that there was a strong competitive adsorption between IPA and acetone, and the adsorption capacity of IPA was significantly higher than that of acetone. During this period, part of the IPA was oxidized to acetone, which caused a significant decrease in the adsorption amount of acetone and continued release due to occupying part of the acetone adsorption sites. At the same time, in an acetone atmosphere, NTP produced a close amount of CO₂ under unit energy input, indicating that the production of CO₂ depends on the S2 adsorption sites [118,119] that can adsorb acetone. Therefore, increasing the number of S2 adsorption sites is also a solution for improving CO₂ selectivity. Karupiah et al. [86] studied the

performance of a $\text{TiO}_2/\text{MnO}_x$ -modified catalyst in the degradation of dilute benzene under DBD plasma photoelectric catalysis. During the degradation process of dilute benzene, the in-situ growth of ozone on the surface of MnO_x led to the generation of atomic oxygen, and the main function of TiO_2 was to generate ultraviolet light-induced catalytic oxidation. The organic combination of the two materials achieved the best photoelectric catalytic effect. Guaitella et al. [107] studied the photoelectrocatalytic degradation of C_2H_2 by the hybrid material of TiO_2 and glass fiber under DBD and UV. The results showed that the removal of C_2H_2 by the porous structure of the hybrid material depends on the generation of oxygen atoms on the surface of the material. Under the condition of external UV, the photocatalytic performance of the TiO_2 material surface to the plasma inherent discharge excitation was weak, but it relied heavily on the activation of the photocatalytic performance of the external UV. The combination of a ferroelectrics-type catalyst and DBD is mainly manifested by the high dielectric constant of the material. A higher dielectric constant can usually generate greater electric field strength and more micro-discharges in the plasma discharge section to improve the synergistic catalytic effect. Jiang et al. [98] explored the effect of BaTiO_3 catalyst packed-bed DBD reactor on the degradation of benzene. The experimental results show that, in the quartz medium reactor, under the conditions of BaTiO_3 catalyst filling, it showed better benzene degradation performance, but the performance in energy yield was poor. Zhu et al. [99] compared toluene degradation under four DBD packed-bed process conditions: no filler, ceramic ring, BaTiO_3 ring, and $\text{Ba}_{0.8}\text{Sr}_{0.2}\text{Zr}_{0.1}\text{Ti}_{0.9}\text{O}_3$ ring. Through comparison, it was found that the degradation efficiency of toluene in the catalytic system filled with $\text{Ba}_{0.8}\text{Sr}_{0.2}\text{Zr}_{0.1}\text{Ti}_{0.9}\text{O}_3$ ring could reach 97%, and the energy efficiency brought by this catalyst was also higher than that under other filling conditions. This is because the collision of high-energy electrons with gas under the modified catalytic system produces more active free radical groups. These active particles can further react with toluene and, simultaneously, improve the degradation efficiency and mineralization rate of toluene. Jeong et al. [97] explored the degradation efficiency of toluene by ferroelectric catalysts supported by different metal oxides at a voltage of 5 kV. The order of catalyst activity was $\text{MnO}_2/\text{BaTiO}_3 > \text{Co}_3\text{O}_4/\text{BaTiO}_3 > \text{CuO}/\text{BaTiO}_3 > \text{BaTiO}_3$; among them, $\text{MnO}_2/\text{BaTiO}_3$ showed a good activity life during the 230 h catalyst activity test, and the degradation efficiency did not decrease. Simultaneously, the $\text{MnO}_2/\text{BaTiO}_3$ catalyst also showed good performance in ozone degradation.

Figure 7. Basic principle of PCO for removal of VOCs, reproduced with permission from [116], 2018, Elsevier.

Table 7. TiO₂ photocatalytic oxidation process for the degradation of VOC pollutants.

Reactions	Equation Number
$\text{TiO}_2 + h\nu \rightarrow e_h^+ + e^-$	1
$\text{O}_2 + e^- \rightarrow \text{O}_2^-$	2
$\text{H}_2\text{O} + e^- \rightarrow \text{OH}^-$	3
$\text{VOCs} + \text{O}_2^- + \text{OH}^- \rightarrow \text{H}_2\text{O} + \text{CO}_2 + \text{by-products}$	4

Note: where e_h^+ and e^- are electron hole and electron, respectively; $h\nu$ is light energy.

4.2.3. Summary

In the research of DBD plasma synergistic titanium-containing catalysts, the target pollutants were mainly aromatics, ketones, aldehydes, alcohols, alkanes, alkenes, and halocarbons, etc. The most studied was the degradation of aromatics, which may be attributed to the ubiquitous characteristic of aromatics in our lives. In addition, the organic compound has the greatest impact on human health. However, there are relatively few studies on halocarbons in this field. Halocarbons are oxidized in the atmosphere to various chlorinated by-products, which will harm human health while also having a huge impact on the ecological environment. Therefore, researchers also need to pay more attention to the degradation of halocarbons. From the perspective of titanium-containing catalysts, the three types of catalyst play different roles in the DBD plasma catalytic system. Titanium-supported catalysts mainly rely on the good dielectric properties of the surface, titanium-containing materials to improve the degradation efficiency of pollutants. Additionally, the support of titanium enhances the formation of catalyst surface active groups, thereby increasing the mineralization rate and inhibiting the formation of harmful by-products. The degradation of VOCs by a TiO₂-supported catalyst depends on its good photoelectric catalytic properties; ferroelectrics-type catalysts also rely on the higher dielectric constant of the catalyst and, simultaneously, this type of catalyst has good performance in the degradation of harmful by-products and the degradation of ozone. Therefore, under the photoelectric catalytic system of DBD and a titanium-containing catalyst, researchers can not only conduct in-depth research on a single type of catalyst, but also combine different types of catalyst. In this way, the advantages of different types of catalyst in the DBD system can be maximized; while researchers maximize the degradation efficiency of VOCs, they also need to consider the degradation of harmful by-products and ozone.

4.3. Future Prospects

The combination of DBD with titanium-containing catalysts has great advantages in the degradation of VOCs, because it has a certain role, not only in electrocatalysis but also in photocatalysis. Most scholars' research in this area mainly relies on changing the inherent properties of catalysts to achieve the degradation of VOCs. However, the research in this area has been relatively mature. We believe that this field can be further studied in the future through the combination of different types of material and the increase of the light energy released by the discharge by changing the reactor structure. (1) Combining different types of catalyst refers to combining two types of material with different properties to maximize the properties of the two materials. For example, the sol-gelling material can be coated on the molecular sieve material. The coating material has photoelectric catalytic properties. On the other hand, the molecular sieve material can increase the contact area between the coating material and the VOCs, so that the two materials can play the greatest role, and the effect of one plus one is greater than two. (2) In terms of changing the structure of the reactor to increase the light energy released by the discharge, the light energy can be retained and the energy loss caused by the light energy escape can be reduced by changing the light reflecting ability of the barrier dielectric material and the electrode material of the reactor. We believe that these research directions will definitely become research hotspots, and we firmly believe that more and more scholars will be interested in these research directions in the future.

5. Conclusions

This paper conducts a bibliometric analysis of 1181 academic papers related to “application of plasma in the field of VOCs” from 1997 to 2021 and draws the following conclusions: (1) Articles in this field have been on the rise since they first appeared in 1992. Especially in recent years, they have become a research hotspot among scholars; (2) From the analysis of national and institutional data, China and its corresponding affiliated institutions have a much higher number of publications than other countries and regions, indicating that China has a leading position in the research field. Although the United States, France, and Japan have less research than China, they also have great influence; (3) From the perspective of journals and disciplines, research in this field is mainly focused in the discipline of engineering, chemistry, physics, environment, and other disciplines and journals, accounting for nearly 70%; (4) Through the analysis of the author’s keywords in the articles, it can be found that high-frequency keywords include “non-thermal plasma”, “dielectric barrier discharge”, “toluene”, “ozone”, “catalyst”, and “TiO₂”. It shows that the research hotspot in this field is the catalytic degradation of VOCs in the cooperation of low-temperature plasma of dielectric barrier discharge and catalysts. The high frequency of TiO₂ catalysts illustrates the research interest of titanium-containing catalysts in this field; the cluster map of the authors’ keywords also proves this point. This article also reviewed the hotspots through keyword analysis and summarized and analyzed related research. It was found that plasma is the most widely used in the field of VOCs; researchers continue to optimize specific processes and catalysts, making the research in this field more forward-looking.

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