Research Photocatalytic Water-splitting based on big data mining technology

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Abstract. Visible photocatalytic water splitting is an effective way to solve the global energy and environmental crisis, and its green and environmentally friendly properties are worth researching. In this paper, we extracted 8395 articles from the core collection of Web of Science from 1991 to 2020. Visual analysis of the data by various software, such as Excel, Origin, Citespace V, reflected the following results. First, the number of related papers has increased exponentially, reaching a peak in 2018, with a total of 1508; next, among all countries, China has published the most papers and cooperated most closely with other countries; additionally, in terms of journals, Applied Catalysis B: Environment has the largest number of publications in the field of visible light catalytic cracking of water, and Journal of the American Chemical Society has the highest number of co-citations in this field, researchers can focus on these journals; finally, MAEDA K, ZHANG J, and WANG Y are ideal collaborators in this field. "Application and modification of graphite phase carbon nitride," "application and modification of Z-scheme photocatalyst," and "band structure engineering" are the hottest research frontiers in this field and represent the future development direction of this field.

1. Introduction

Visible light energy, as a type of renewable energy, can be converted into chemical energy, and promises great potential in alleviating global energy problems[1]. Inspired by natural photosynthesis, researchers found that sunlight-driven water splitting is an ideal way to convert visible light energy into usable hydrogen energy[2]. This method exhibits more environmentally friendly and economical than other means such as high-temperature hydrogen production.

As a prelude of photocatalytic technology, in 1972, Fujishima and Honda[3] reported for the first time the use of n-TiO₂ cells with Pt to photocatalytic split water to produce hydrogen. And in the past 40 years, various available semiconductor materials, such as TiO₂, CdS, BiVO₄, Ta₃N₅, g-C₃N₄, have been extensively used as photocatalysts, directly using visible light energy to carry out different redox reactions[4]. However, there remain challenges for most photocatalysts to achieve sunlight-driven water splitting without using sacrificial agents, and their catalytic efficiency is also far from reaching actual application requirements[5]. In addition, photocatalysts need to have a suitable energy-band structure to absorb enough visible-light[6], and more importantly, it must effectively separate and transmit photogenerated electrons and holes, and has efficient and stable active sites for hydrogen and oxygen production at the same time[7]. Therefore, the search for new efficient, stable and inexpensive photocatalysts is a trend in this field[8].

Recently, to improve visible light energy utilization efficiency, various researches were conducted. some articles described the mechanism, research status and development of visible photocatalytic water-
splitting. Unfortunately, there is few bibliometrics reports on this field in literature so far. Herein, we use Citespace V and other software to conduct a scientific visual analysis of the research status in this field, in order to explore the current research frontiers in this field and provide scientific and reliable theoretical support for researchers in this field.

2. Methods and data

2.1. Sources of data and searching strategies
The information of the articles is from Web of Science Core Collection (hereinafter referred to as WOSCC) database, which contains timely updating, high quality and comprehensive coverage, and has high authoritative in the existing literature retrieval database. Research data acquisition was divided into two steps. The first step was: in the WOS literature retrieval platform, Select the "WOS core collection" database. The Boolean operation rules for design retrieval are: ((TS=(visible light catalysis AND H2O splitting) OR TS=(visible light catalysis AND water splitting) OR TS=(visible light catalysis AND hydrogen generation) OR TS=(visible Photocatalytic water splitting) OR TS=(visible photocatalytic hydrogen production))).

To prevent missing data, all indexes of WoSCC were used. These indexes include SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC.

In order to avoid errors caused by updating the database, all paper searches and data downloads were completed on June 22, 2020. A total of 9781 bibliographic records were collected from 1991 to 2020.

In order to prevent the deviation of the results, we chose to exclude other types of documents. Then only 8594 articles were used to analyze. The excluded types of documents were: REVIEW, PROCEEDINGS PAPER, BOOK CHAPTER, EARLY ACCESS, MEETING ABSTRACT, EDITORIAL MATERIAL, CORRECTION, BOOK OR LETTER, RETRACTED PUBLICATION.

The second step was: two authors independently completed data download and screening, and finally jointly confirmed that 8594 articles met the requirements of the subject. The records of the retrieved documents were downloaded and saved as pure text files in the form of "summary and full record (including references)". After downloading, the above articles were re-examined, and after repeating the duplicated articles, 8395 effective articles were obtained as a sample of the research analysis data.

2.2. Sources of data and searching strategies
First, we imported the extracted annual data of publications into Origin Pro 2019b to analyze the annual trend of the number of papers. Next, the information of article citation was imported into Microsoft Office Excel 2019, which was used to visualize the annual citation rules. And then the maps of the cooperation relationship between the countries and regions were described by the online analysis platform (http: bibliometric.com) according to the data of publications. Finally, we imported the complete paper information into the CiteSpace V software, and perform a bibliometric analysis of the countries, institutions, journals, authors, document clusters, and emerging documents in the field.

3. Results
We imported all the information of 8375 documents into citespace V for analysis, and obtained country collaboration network (Figure 1(a).), institution collaboration network (Figure 1(b).), journal co-citation network (Figure 1(c).), author co-citation network (Figure 1(d).), and literature co-citation network (Figure 2.). According to these network analyses, China (centrality=0.16), Germany (centrality=0.16), the USA (centrality=0.17) and India (centrality=0.17) have occupied key positions in the network and their research cooperation relationships in this field are closer than other countries. Chinese Acad Sci was the largest contributor, publishing 738 Articles, followed by Fuzhou Univ (260), Univ Chinese Acad Sci (190). The centrality values indicated that Chinese Acad Sci (0.46) worked closely with other institutes. Applied Catalysis B: Environment published the most articles (IF-2018: 6.203; 599 articles, 6.9%), followed by International Journal of Hydrogen Energy (IF-2018: 5.252; 586 articles, 6.8%), and RSC Advances (IF-2018: 5.252; 332 articles, 3.8%). In terms of papers, DOMEN K
ranked first (122 articles; 1.4%), followed by ZHANG J (113 articles; 1.3%), and WANG Y (112 articles; 1.3%). In the term of co-citation count, FUJISHIMA A was the most prominent author with 2,608 co-citations, followed by KUDO A (2,190) and MAEDA K (2,017).

The paper co-citation network shows that the research topics in the field of visible light splitting water are mainly "graphene nanocomposites", "graphene carbon nitride", "visible-light irradiation", etc.

In the term of references with citation bursts, the citations of 26 references are still rising sharply until 2020 (Table 3.), and they reflect the recent development direction and research hotspots in this field.

Figure 1. (a) A visualization of the country collaboration network (1991-2020). (b) A visualization of the institution collaboration network (1991-2020). (c) A visualization of the journal co-citation network (1991-2020). (d) A visualization of the author co-citation network (1991-2020).
Figure 2. A visualization of the literature co-citation network (2015-2020)

Table 1. The top 10 most productive authors.

| Rank | Author  | Count | % of 8595 |
|------|---------|-------|------------|
| 1    | DOMEN K | 122   | 1.419      |
| 2    | ZHANG J | 113   | 1.315      |
| 3    | WANG Y  | 112   | 1.303      |
| 4    | LIU Y   | 109   | 1.268      |
| 5    | LI Y    | 99    | 1.152      |
| 6    | WANG L  | 98    | 1.14       |
| 7    | GUO LJ  | 88    | 1.024      |
| 8    | LI C    | 85    | 0.989      |
| 9    | MAEDA K | 85    | 0.989      |
| 10   | WANG H  | 83    | 0.966      |

Table 2. Top 10 authors with most co-citation count.

| Rank | Count | Centrality | Cited Authors     |
|------|-------|------------|-------------------|
| 1    | 2608  | 0.17       | FUJISHIMA A       |
Table 3. 26 References with the Strongest Citation Bursts lasting until 2020.

| Rank | References | Year | Strength | Begin | End | 2015 - 2019 |
|------|------------|------|----------|-------|-----|-------------|
| 1    | Ong WJ, 2016, CHEM REV, V116, P7159 | 2016 | 37.2444  | 2018  | 2020 | ▂▂▂▃▃▃     |
| 2    | Low JX, 2017, ADV MATER, V29, P0   | 2017 | 31.0867  | 2018  | 2020 | ▂▂▂▃▃▃     |
| 3    | Yu HJ, 2017, ADV MATER, V29, P0   | 2017 | 28.8617  | 2018  | 2020 | ▂▂▂▃▃▃     |
| 4    | Liang QH, 2015, ADV FUNCT MATER, V25, P6885  | 2015 | 19.9905  | 2018  | 2020 | ▂▂▂▃▃▃     |
| 5    | Wen JQ, 2017, APPL SURF SCI, V391, P72   | 2017 | 19.4163  | 2018  | 2020 | ▂▂▂▃▃▃     |
| 6    | Zhu MS, 2017, J AM CHEM SOC, V139, P13234  | 2017 | 19.3873  | 2018  | 2020 | ▂▂▂▃▃▃     |
| 7    | Che W, 2017, J AM CHEM SOC, V139, P3021  | 2017 | 18.4139  | 2018  | 2020 | ▂▂▂▃▃▃     |
| 8    | Yi SS, 2017, APPL CATAL B-ENVIRON, V200, P477  | 2017 | 17.8362  | 2018  | 2020 | ▂▂▂▃▃▃     |
| 9    | Marshall R, 2014, ADV FUNCT MATER, V24, P2421  | 2014 | 17.8362  | 2018  | 2020 | ▂▂▂▃▃▃     |
| 10   | Zhang GG, 2017, ANGEW CHEM INT EDIT, V56, P13445  | 2017 | 17.2587  | 2018  | 2020 | ▂▂▂▃▃▃     |
| 11   | Lin LH, 2016, ACS CATAL, V6, P3921   | 2016 | 16.97    | 2018  | 2020 | ▂▂▂▃▃▃     |
| 12   | Yu WL, 2017, APPL CATAL B-ENVIRON, V219, P693  | 2017 | 16.5754  | 2018  | 2020 | ▂▂▂▃▃▃     |
| 13   | Wen JQ, 2017, ACS APPL MATER INTER, V9, P14031  | 2017 | 15.8156  | 2018  | 2020 | ▂▂▂▃▃▃     |
| 14   | Kang YY, 2015, ADV MATER, V27, P4572  | 2015 | 15.3717  | 2018  | 2020 | ▂▂▂▃▃▃     |
| 15   | Wang K, 2015, APPL CATAL B-ENVIRON, V176, P44  | 2015 | 14.1689  | 2018  | 2020 | ▂▂▂▃▃▃     |
| 16   | Fu JW, 2017, SMALL, V13, P0    | 2017 | 13.7681  | 2018  | 2020 | ▂▂▂▃▃▃     |
| 17   | Niu P, 2012, J PHYS CHEM C, V116, P11013  | 2012 | 12.5664  | 2018  | 2020 | ▂▂▂▃▃▃     |
| 18   | Ran JR, 2015, ENERG ENVIRON SCI, V8, P3708  | 2015 | 9.3913   | 2018  | 2020 | ▂▂▂▃▃▃     |
| 19   | Han Q, 2016, ACS NANO, V10, P2745  | 2016 | 9.3594   | 2018  | 2020 | ▂▂▂▃▃▃     |
| 20   | Wang Q, 2016, NAT MATER, V15, P611  | 2016 | 8.4842   | 2018  | 2020 | ▂▂▂▃▃▃     |
| 21   | Yu JG, 2013, PHYS CHEM CHEM PHYS, V15, P16883  | 2013 | 7.8792   | 2018  | 2020 | ▂▂▂▃▃▃     |
| 22   | Zhang GG, 2016, CHEM SCI, V7, P3062  | 2016 | 7.7851   | 2018  | 2020 | ▂▂▂▃▃▃     |
| 23   | Zhang LJ, 2014, ACS CATAL, V4, P3724  | 2014 | 7.6369   | 2017  | 2020 | ▂▂▂▃▃▃     |
| 24   | Li JH, 2012, CHEM COMMUN, V48, P12017  | 2012 | 7.4316   | 2018  | 2020 | ▂▂▂▃▃▃     |
| 25   | Guo SE, 2016, ANGEW CHEM INT EDIT, V55, P1830  | 2016 | 7.3531   | 2018  | 2020 | ▂▂▂▃▃▃     |
| 26   | Dong F, 2013, ACS APPL MATER INTER, V5, P11392  | 2013 | 3.0363   | 2018  | 2020 | ▂▂▂▃▃▃     |

4. Conclusions

Countries paid great attention to visible photocatalytic water splitting and invested massive amounts. With the most volume of articles published (6.77 times that of the USA), China exhibited a significant
advantage in this field. The top 10 institutions are all among Asia and 8 of them among China. The Chinese Acad Sci, which has the largest number of posts and close cooperation, exhibited significant influence. Applied Catalysis B: Environment was the top source journal in visible photocatalytic water splitting, and Journal of the American Chemical Society was the top co-cited journal, and they have occupied a key position in this field. Through the analysis of the author co-cited, results indicated that MAEDA K, ZHANG J, WANG Y were ideal collaborators in this field.

To date, "Application and modification of graphite carbon nitride," "application and modification of Z-scheme photocatalysts," "energy band structure engineering" are the research frontiers in this field. Relevant research is gradually being carried out, and significant progress may be made in the future. This research made a detailed analysis of the material selection and modification methods for visible light hydrogen production. It has important guiding significance for the development of related research, especially the research on reducing costs and improving efficiency.

Note
The authors promise that there are no competing financial interests.

Author Information
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References
[1] Hosseini S E and Wahid M A 2020 Hydrogen from solar energy, a clean energy carrier from a sustainable source of energy International Journal of Energy Research 44 4110–4131
[2] Zhang M, Lu M, Lang Z-L, Liu J, Liu M, Chang J-N, Li L-Y, Shang L-J, Wang M and Li S-L 2020 Semiconductor/Covalent-Organic-Framework Z-Scheme Heterojunctions for Artificial Photosynthesis Angewandte Chemie International Edition 59 6500–6506
[3] Fujishima A and Honda K 1972 Electrochemical photolysis of water at a semiconductor electrode nature 238 37–38
[4] Wen J, Li X, Liu W, Fang Y, Xie J and Xu Y 2015 Photocatalysis fundamentals and surface modification of TiO2 nanomaterials Chinese Journal of Catalysis 36 2049–2070
[5] Hisatomi T, Kubota J and Domen K 2014 Recent advances in semiconductors for photocatalytic and photoelectrochemical water splitting Chemical Society Reviews 43 7520–7535
[6] Tang J, Durrant J R and Klug D R 2008 Mechanism of photocatalytic water splitting in TiO2. Reaction of water with photoholes, importance of charge carrier dynamics, and evidence for four-hole chemistry Journal of the American Chemical Society 130 13885–13891
[7] Maeda K and Domen K 2010 Photocatalytic water splitting: recent progress and future challenges The Journal of Physical Chemistry Letters 1 2655–2661
[8] Maeda K 2011 Photocatalytic water splitting using semiconductor particles: history and recent developments Journal of Photochemistry and Photobiology C: Photochemistry Reviews 12 237–268