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Review article

Research progress, trends, and updates on pollutants removal by Bi_2WO_6-based photocatalysts under visible light irradiation

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ABSTRACT

In recent years, extensive research has been conducted on bismuth tungstate (Bi_2WO_6) in the field of photocatalysis owing to its unique crystal structure and favorable bandgap. This study offers a comprehensive review of the research on Bi_2WO_6-based photocatalysts from 2007 to 2022 using bibliometric analysis. The analysis utilized the Web of Science Core Collection Database and encompassed a dataset of 2064 publications. The bibliometric analysis and science mapping were carried out using the bibliometix R-package and CiteSpace software. This analysis examined and discussed the network of relationships among countries, journals, organizations, authors, and keywords pertaining to the topic and subtopics under investigation. The findings demonstrate that China has played a significant role in this research area and has formed close collaborations with other countries. The identification of highly-cited emerging terms suggests that enhancing the photocatalytic performance of Bi_2WO_6-based nanomaterials is a primary research focus. Moreover, there has been increasing interest in exploring the synergistic effects of photocatalysis and adsorption as a means to improve catalytic efficiency. This study provides valuable insights for researchers seeking a deeper understanding of Bi_2WO_6-based photocatalysts.

1. Introduction

As early as 1972, the phenomenon that water can be split into oxygen and hydrogen gases (O_2 and H_2) by ultraviolet (UV) irradiation of a single-crystal titanium (IV) oxide (TiO_2) anode was found by Fujishima and Honda [1]. Since then, a great deal of research has been devoted to semiconductor photocatalysis [2–4]. Thanks to nearly four decades of efforts by researchers worldwide, semiconductor photocatalysis have been playing important roles as an efficient advanced oxidation technology in many fields, such as environmental remediation, agricultural cultivation, energy conversion, and medical care [5–8]. However, many of these catalysts are only active under UV irradiation because of their wide band gaps, such as TiO_2 [9] and ZnO [10]. Clearly, the narrow light response range of photocatalytic materials greatly limits utilization of the sunlight, as visible light accounts for 43% of the whole solar spectrum [11]. Over past decades, in order to utilize solar energy as much as possible, many photocatalysts with high visible light activity have been developed [12,13].

Recently, due to their unique crystal structure and suitable bandgap, bismuth (Bi)-based semiconductor photocatalysts have been widely used in the photocatalysis area [14–16], such as bismuth molybdate [17], bismuth tungstate [18,19], bismuth hypohalites [20],

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bismuth vanadate [21], and bismuth oxide [22] (Bi_2MoO_6, Bi_2WO_6, BiOX (X = Cl, Br, or I), $BiVO_4$, and Bi_2O_3, respectively). Among these, Bi_2WO_6 has attracted much attention due to its excellent visible light photocatalytic activities, unique layered structure, high thermal and photochemical stabilities, and environmental friendliness [23,24]. Bi_2WO_6 shows a visible-light absorption edge at ~470 nm with a band gap located at ~2.8 eV Bi_2WO_6 is constructed of perovskite-like $[WO_4]^{2-}$ layers sandwiched between $[Bi_2O_2]^{2+}$ layers, which is beneficial for separating photoexcited electron-hole pairs, and then enhancing photocatalytic performance [25,26].

Though the morphological control and atomic modulation of Bi_2WO_6 greatly improved its photocatalytic activity, the separation efficiency of photogenerated carriers is not satisfactory because there is only one component in the photocatalytic system and the charge recombination possibility remains high [27]. Fabrication of composite photocatalysts is considered as an effective modification strategy for improving the utilization of solar energy and promoting charge carrier separation [28,29]. For now, the materials that metal-based materials, carbon-based materials, and semiconductors are chosen for coupling Bi_2WO_6 [30–32].

In recent years, a lot of articles have been published regarding the study of photocatalytic efficiency improvement of Bi_2WO_6 based nanomaterials [25,33,34]. Bibliometric analysis can scientifically explain and analyze the research evolution process, research progress, and future development trend of this field through mathematical analysis and statistics of past articles published in this field [35–37]. The objectives of this study were to construct social network maps through bibliometric analysis of existing articles related to Bi_2WO_6-based nanomaterials. It is useful for understanding the history of Bi_2WO_6-based photocatalyst research area, current research hotspots, and future trends. Some suggestions and perspectives were also given by specifically discussing the hot issues of Bi_2WO_6--based photocatalyst.

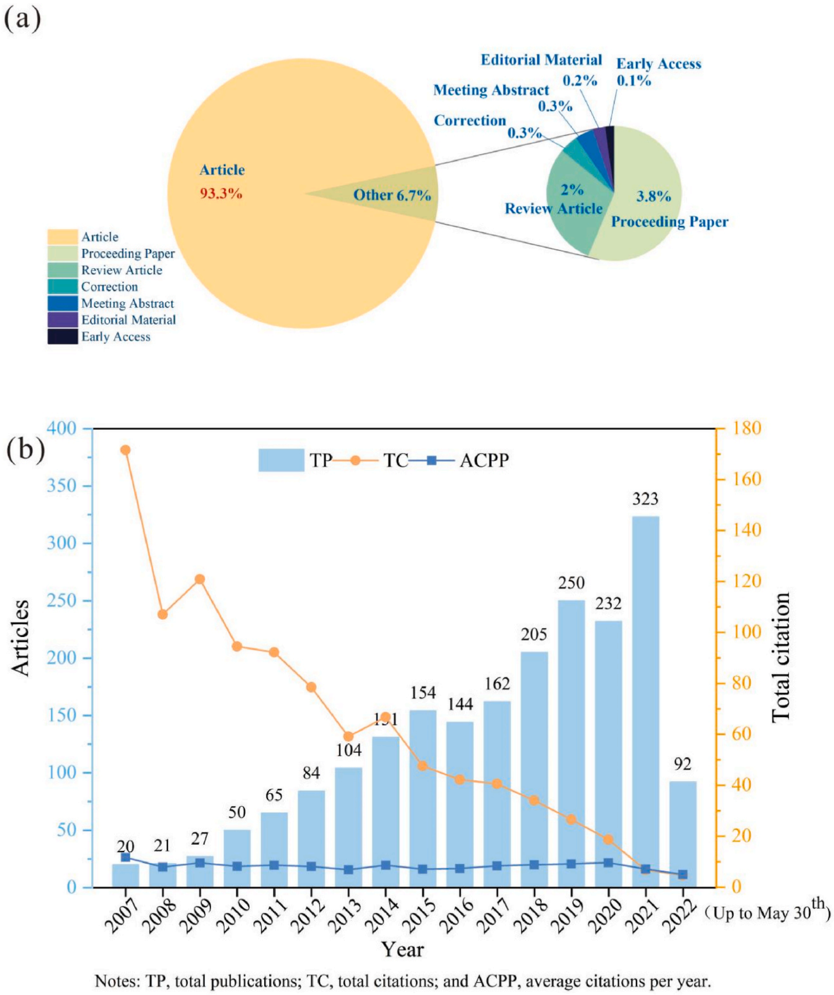


Fig. 1. (a) Distribution of document type related to Bi_2WO_6-based photocatalyst research.
(b) TP, TC, and ACPP statistics in the field of Bi_2WO_6-based photocatalyst from 2007 to 2022.

2. Methods

2.1. Data sources

Reliable data sources with recognized influence should be selected for scientific bibliometrics to ensure the authenticity of data. Web of Science (WoS) contains influential journals in a wide range of subject areas. To obtain more information related to Bi_2WO_6-based photocatalysts, the WoS core collection was selected as the data source for this study. Articles published in the 15 years from 2007 to 2022 were selected on June 6, 2022. Articles with the words “Photocataly*" and " Bi_2WO_6″ in the title, abstract, or keywords of the article were regarded as valid data. Finally, a total of 2064 studies scientific documents were selected and submitted for bibliometric analysis.

2.2. Methods

Bibliometrix is one of the effective methods for statistical analysis, clustering analysis, and visualization processing in the R-language software package [38–40]. Using Bibliometrix, the main research direction of Bi_2WO_6-based photocatalyst was described from different aspects as the reference type, annual production, key word theme, and historical reference quoted.

Rank	From	To	Fre
1	China	USA	46
2	China	Australia	28
3	China	Singapore	16

Fig. 2. Combinatorial mapping and clusters of countries (a) and network of international cooperative relations (b).

CiteSpace software can reveal the scientific knowledge and activities in a visual form [36]. By establishing a cluster analysis of the cooperation network of top 10 countries, institutions, and journals, the cooperative relations of different regions and units were explored. In addition, the research directions and future research hotspots of the subject field were revealed through the time evolution and abruptness of keywords.

In this study, the time threshold of CiteSpace was set at 2007–2022 and the year per slice set at 1. Before visualization analysis, clarity of the atlas was ensured and filtering out as much as possible of information with low relevance in the setting process, papers with the top 50 citations were selected in each section in the Selection Criteria. After setting the threshold, Pathfinder, Pruning sliced networks, and Pruning merged networks were selected and pruned. Then, automatic clustering visual analysis was applied. In the merged relational network, nodes were automatically assembled to form clusters according to their correlations. The size of appearing nodes was proportional to the occurrence frequency and the number of nodes in a cluster arranged backward with #0 as the largest.

3. Results and discussion

3.1. Literature quantity analysis

The types of published articles over 15 years were divided into 9 types, among which journal articles were the most common type, with 1870 articles, accounting for 93.3% of the total (Fig. 1a). Conference proceedings papers (76, 3.8%) accounted for the 2nd largest group, followed by review papers (40, 2.0%) for the 3rd, and the other four categories relatively low. Clearly, journal articles possessed high credibility in the field of Bi_2WO_6-based photocatalyst research. In recent years, Bi_2WO_6 materials have been widely concerned, among which the application of 6 is also worth researchers to discuss, in 1870 research papers Bi_2WO_6 as a photocatalyst material accounted for the main part, as a cutting-edge photocatalytic material has been widely concerned by people.

The statistics of the total number of publications and total number of citations in a year can visually show the research status of Bi_2WO_6-based photocatalyst research in chronological order [41]. From 2007 to 2022, the total number of publications, citations, and average number of citations per year in the field of Bi_2WO_6-based photocatalysts showed that the total number of published papers grew rapidly over the past 15 years (Fig. 1b.). However, the first three years (2007–2009) produced <1% of the total number of articles published. Since 2013, the number of publications has increased sharply. The total number of papers published in the nine years from 2013 to 2022 (1797 papers) was 6.7 times the total number of papers (267) in the first six years (2007–2012). This showed that research on Bi_2WO_6-based photocatalysts was in a rapid stage of development. Among them, the publication of papers on Bi_2WO_6 materials reached the highest value in 2022, mainly because the excellent performance of Bi_2WO_6 has been widely concerned by researchers, and it also shows that researchers have great interest in the material. The total citation volume of articles in this field showed a downward trend year by year, which might have been caused by the time factor. Generally speaking, the citation frequency of an article is positively correlated with the length of publication time. The earlier the article is published, the higher the citation frequency will be, while a newly published journal needs to be cited in new articles through accumulated later time [42]. This may be due to the fact that China currently dominates the field, but cooperation is still limited.

3.2. Active countries, institutions, and authors

3.2.1. Contribution of different countries

Fig. 2 a collinear map of countries is drawn using CiteSpace software, where the lines represent the meaning of joint development of photocatalyst research for Bi_2WO_6 between countries. On the periphery of the country, there are rings with different colors. The size of the circle indicates that the country has received extensive attention from researchers in recent years, and the larger the circle indicates that the country has more output of articles on Bi_2WO_6 materials. The color of the outer circle also has different representative meanings, and the color gradually brightened from the inside to the outside, representing the country's research on Bi_2WO_6 materials is of great significance. By running the "country" as the node in CiteSpace software and plotting the geographical distribution of research studies on Bi_2WO_6-based photocatalyst research yielded Fig. 2 a. In addition, the information regarding the top 10 countries in terms of publication numbers is shown in Table 1. In the past 15 years, 64 countries have conducted research in this field and a total of 2064 articles published. The top 10 countries accounted for 93.61% of the total. China, India, the United States, South Korea, and

Table 1
Top 10 countries by article production, 2007–2022.

Rank	TP	Centrality	Country	Year
1	1465	0.53	China	2007
2	78	0.19	India	2012
3	59	0.29	USA	2011
4	52	0.23	South Korea	2009
5	48	0.06	Thailand	2013
6	38	0.12	Japan	2007
7	31	0.00	Australia	2010
8	30	0.13	Iran	2011
9	23	0.09	Saudi Arabia	2013
10	22	0.01	Canada	2015

Thailand rounded out the top five. P. R. China was observed to have published the most articles in this field (1465 articles), accounting for 74.18% of the total literature, followed by India (78) and the United States (59), at far less than China.

The centrality in Table 1 well demonstrated the influence of this research in the field of Bi_2WO_6-based photocatalysts and was considered to have a strong influence when the centrality was >0.1. The centrality of the top three countries (China, India, and the US) in article production were 0.53, 0.19, and 0.29, respectively, indicating that they have formed close academic cooperation networks with other countries and had certain academic recognition. Notably, the number of publications in the US was only 1/24th of that in China, but it still had high centrality. The reason for this phenomenon might have been because the US has more authoritative publications.

Social Network Analysis (SNA) can be used to accurately quantify the relationship between cooperative institutions and cooperative countries [43–45]. The mapping cluster and cooperation network among the top 10 countries in production capacity are shown in Fig. 2 b, in which each node represents a country and line represents cooperation between countries. The results indicated that China has maintained close cooperation with other countries, among which it has the closest cooperation with the US, publishing 46 papers. In addition, the frequency of cooperation with Australia, Singapore, and Japan was 28, 16, and 14 times, respectively. Clearly, compared with developing countries, China has closer exchanges and cooperation with developed countries in the field of Bi_2WO_6 photocatalyst research, which was helpful for improving research quality. According to the contents of Fig. 2 a-b and Table 1, China occupies a leading position in the research field of Bi_2WO_6 photocatalyst. Secondly, the journal papers published in China are also of great research significance. Although the number of research publications in the United States is small, the depth of research has a unique insight, and it is also worth learning for new researchers who pay attention to Bi_2WO_6.

3.2.2. Contribution of different institutions

According to the statistical results, a total of 1167 institutions have published articles in the field of Bi_2WO_6-based photocatalysts. Combinatorial illumination and clustering of institutions showed that the Chinese Academy of Sciences (CAS) was at the core of the institutional cooperation network and maintained close cooperation with many domestic institutions, such as Jiangsu University and Tsinghua University (Fig. 3). This was because the CAS has more than 100 branches in many cities across the country, such that it has more opportunities to cooperate with many universities [46,47]. However, the CAS has few partnerships at present with overseas institutions. While maintaining cooperation with other domestic institutions, the Beijing University of Technology has also developed a good cooperative relationship with the Prince Songkhla University of Thailand, which has been conducive to mutual exchange and learning.

There has been continuous attention and research focused on improving the photocatalytic performance of Bi_2WO_6-based nanomaterials in China in the past 15 years (Table 2). The CAS, which started research in the field in 2007, has maintained the highest output (122). The rest of the top five in research production were Jiangsu University (53), Tsinghua University (50), Jilin University (43), and Chiang Mai University (41), accounting for 30.58% of the total number of publications. Notably, Tsinghua University ranks 3rd in the number of articles published, but has the highest centrality (0.17), which indicated that the article quality of Tsinghua

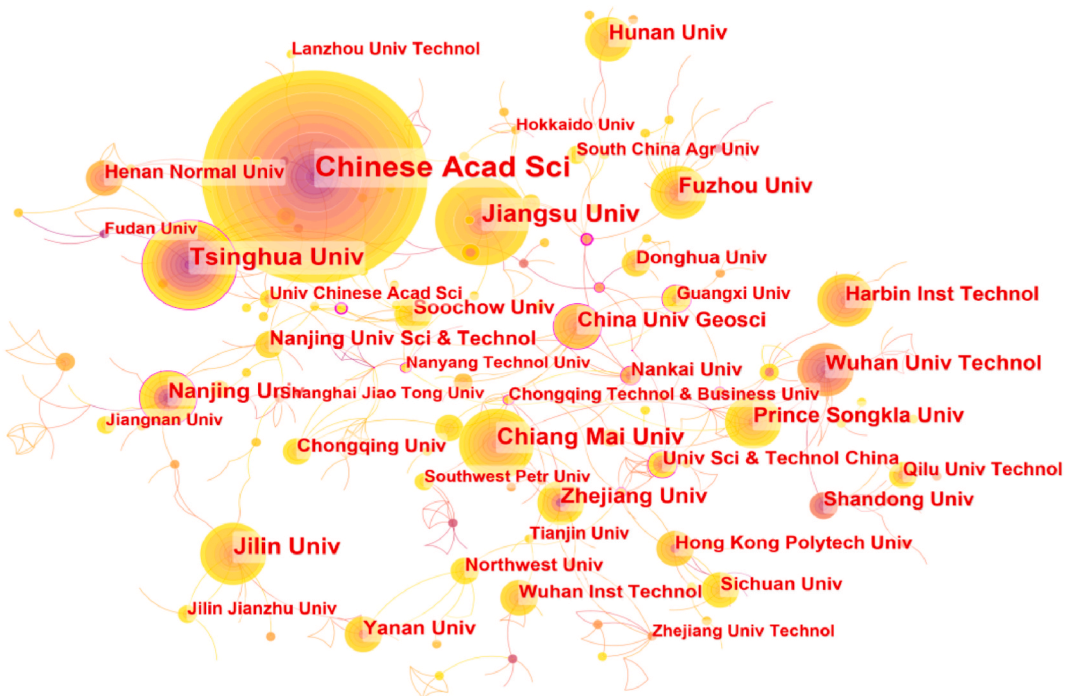


Fig. 3. Combinatorial mapping and clustering of institution.

Table 2
Top 10 institutions of article production, 2007–2022.

Rank	TP	Centrality	institution	Year
1	122	0.09	Chinese Acad Sci	2007
2	53	0.06	Jiangsu Univ	2008
3	50	0.17	Tsinghua Univ	2007
4	43	0.04	Jilin Univ	2008
5	41	0.02	Chiang Mai Univ	2013
6	34	0.06	Zhejiang Univ	2008
7	33	0.09	Fuzhou Univ	2009
8	31	0.14	Nanjing Univ	2008
9	30	0.08	Wuhan Univ Technol	2008
10	29	0.03	Prince Songkla Univ	2013

University was more highly recognized and authoritative in this research field. Of the top 10 institutions, eight were from China and all started their studies before 2010. The other two were Chiang Mai University and Prince Songkhla University in Thailand, both of which started their research in this field in 2013. In general, compared with other countries, China has been in the field of Bi_2WO_6-based photocatalyst earlier and has paid more attention.

3.2.3. Contribution of different authors

According to statistics, a total of 3769 authors have published articles related to Bi_2WO_6-based photocatalysts. The academic collaboration between authors of relevant articles showed almost no isolated nodes in the network of collaborative relationships, indicating that the development and improvement of the field largely depended on mutual cooperation between research teams, rather than independent teams (Fig. 4).

The Hirsch (h)-index is a method used to evaluate the scientific academic achievements of authors [36]. The darker the circle is, the higher the h-index value. The author rankings of the h-index from highest to lowest in terms of literature produced in the field of Bi_2WO_6-based photocatalyst are shown in Fig. 5. Considering the ranking of cited authors, Zhang L. started his research in this field in 2007 and the citation volume, production, and h-index of his articles the highest, followed by Wang W., indicating that they have made important contributions to the field of Bi_2WO_6-based photocatalysts (Table 3). In 2007, Zhang L et al. published a study on Bi_2WO_6 in the Journal of Materials Chemistry, which attracted wide attention from scholars. The study used a simple hydrothermal process and did not require any surfactants or templates to successfully achieve the preparation of a novel flower-like Bi_2WO_6 superstructure. In addition, the law of the change of Bi_2WO_6 morphology with hydrothermal time was revealed, and the mechanism of its formation was

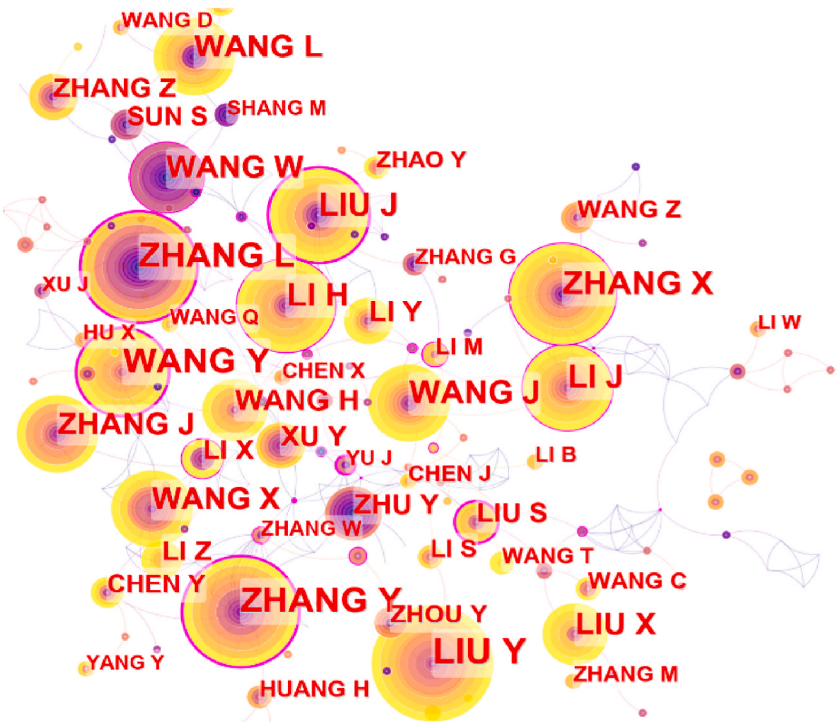


Fig. 4. Combined priming and clustering of related authors.

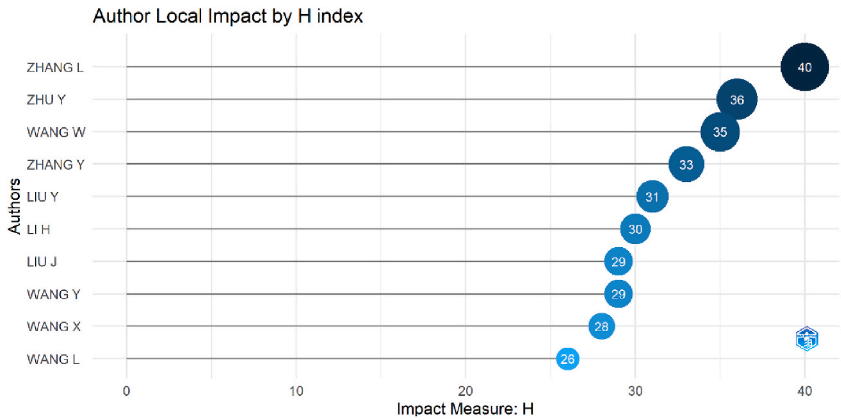


Fig. 5. Influence of the top 10 most cited.

Table 3
Top 10 authors with most articles produced and cited, 2007–2022.

Rank	TC	TP	Centrality	Author	Year
1	8968	94	0.30	ZHANG L	2007
2	6398	65	0.23	LIU J	2007
3	5485	49	0.04	ZHU Y	2007
4	5327	69	0.13	WANG W	2007
5	5240	55	0.09	WANG X	2007
6	5175	94	0.25	ZHANG Y	2008
7	4689	56	0.10	WANG H	2011
8	4523	28	0.00	CHEN Z	2007
9	3965	29	0.03	LI S	2011
10	3903	72	0.14	LI H	2010

clarified. In the hydrothermal process, with the increase of hydrothermal time, the nanoparticles continue to aggregate into spherical particles, accompanied by the evolution from solid spherical particles to spherical superstructure. When the hydrothermal time continues to extend, due to mass diffusion and Ostwald maturation, the formation of Bi_2WO_6 becomes more and more complex. The solid spherical particles are depleted and a large number of Bi_2WO_6 nanosheets are formed. For spherical formation, the geometric constraints of building blocks should play a key role. By comparison, it was found that the degradation of Rhodamine B by Bi_2WO_6 calcined at 550 °C could reach 97% within 60 min, which showed excellent performance compared with the photocatalytic materials of the same period. It has been found that the main reason for the degradation is that its special synthesis method makes a large number of pores of different sizes exist in the superstructure of Bi_2WO_6, which can serve as the hierarchical transport path of small molecules and may greatly improve its photocatalytic activity [48]. In the same year, the author also made a study on shape control synthesis and improvement of physical and chemical properties of nano and micron structural materials. In this study, the structural shape of Bi_2WO_6 (flower, tire, spiral and plate shape) was mainly regulated by hydrothermal synthesis. For the first time, the formation of WO6 from a three-dimensional (3D) flower-like superstructure to a 2D plate-like structure, as well as a tire-like and spiral-like Bi_2WO_6 superstructure was discovered. It is found that the optical properties of Bi_2WO_6 are closely related to its size and shape by UV–visible absorption spectra, which also indicates that the nanostructure and microstructure of Bi_2WO_6 are the main factors affecting its photocatalytic activity [49].

In 2014, Zhang L et al. published a new research foreword on semiconductors in Chemical Society Reviews, which has been cited more than 2421 times so far. In this study, the serious shortcomings of fast charge recombination and limited visible light absorption of semiconductor photocatalysts are discussed. In this paper, the rational design and manufacture of many kinds of heterojunction photocatalysts such as semiconductor-semiconductor heterojunction, semiconductor-metal heterojunction, semiconductor-carbon heterojunction and multicomponent heterojunction are summarized. The coupling of semiconductor-semiconductor heterojunction can fully meet the high absorption of solar energy, which can enable the photocatalyst to achieve higher catalytic efficiency. The heterojunction with carbon material can effectively drive the separation and transport of electron-hole pairs, so that the photocatalyst can get the maximum utilization rate. For the deposition of metals and semiconductors to form heterojunctions, it can enhance the utilization of sunlight or improve the separation and transport of electron-hole pairs. The relationship between the environment and new energy applications is also discussed on the connection modes of various heterojunctions, in which different connection modes are targeted at various pollutant degradation systems. Through the summary of the literature system, it is found that the formation of heterogeneous bonds provides a promising way to improve the photocatalytic efficiency of photocatalytic semiconductors [50].

Through the summary of the above literature, it is found that Zhang L has become a representative scholar in the industry through the in-depth research on Bi_2WO_6 materials and the extension of semiconductor materials.

3.3. Analysis of subject journals

3.3.1. Subject analysis

The evolution and development of a discipline should be based on the existing knowledge. According to the citation records of articles in the WoS database, the discipline evolution of the research field can be well understood [51]. The vein diagram of the reference relationships in the field of Bi_2WO_6-based photocatalysts showed citing articles and cited articles (Fig. 6, left and right, respectively). The diagram's curve showed the line of citation to indicated the citation context, with the ellipse size indicating the number of papers and authors published in the journal.

A main citation path was identified in the venation diagram (Fig. 6, purple), indicating that these published research in Physics/Materials/Chemistry, has been often quoted in the published research in Chemistry/Materials/Physics. In addition, there have been a few studies published in Veterinary/Animal/Science, cited by the research published in Environmental Toxicology/Nutrition study. This was because the preparation and application of Bi_2WO_6-based photocatalysts belongs to different fields and the preparation of nanomaterials closely related to material science and chemistry. Thus, most of the articles published in this field were concentrated in disciplinary journals related to chemistry and materials. However, the use of Bi_2WO_6-based photocatalysts was mostly concentrated in the treatment of water environmental pollution, among which livestock and aquaculture wastewater treatments accounts for a large part. Therefore, the application articles of Bi_2WO_6-based photocatalysts were mainly published in the academic journals related to the environment and animals.

3.3.2. Journal analysis

The combined illumination and clustering of highly cited journals showed that the centrality of Applied Catalysis B-Environmental (0.38) and Journal of Physical Chemistry C (0.22) were both greater than 0.1, indicating high recognition in the field compared to other journals (Table 4). Meanwhile, the number of citations of journal articles represented the relevance and importance of the academic community, which directly demonstrated the importance degree and literature quality of the article in the field of Bi_2WO_6-based photocatalytic nanomaterials [52]. The top 10 journals with the most cited and produced articles from 2007 to 2021 showed that the top three cited journals were Applied Catalysis B-Environmental (9301), Journal of Physical Chemistry C (4425), and Applied Surface Science (4386). Among them, Applied Catalysis B-Environmental (IF = 24.319) and Applied Surface Science (IF = 7.392) had high impact factors and part of a growing trend in the past five years. Worthy of mention, the Journal of Materials Chemistry A began to publish articles related to Bi_2WO_6-based photocatalytic nanomaterials in 2013. In the past 15 years, only 20 articles were published, but there were 1691 citations, indicating a high impact factor (IF = 14.511) that effectively guaranteed the quality and credibility of the articles.

3.4. Co-cited and clusters analysis of references

3.4.1. Co-cited analysis

The historical references of Bi_2WO_6-based photocatalytic nanomaterials were directly generated through the Bibliometrix software package and visual analysis carried out. The data were analyzed according to LCS (the number of citations in the current WoS core data

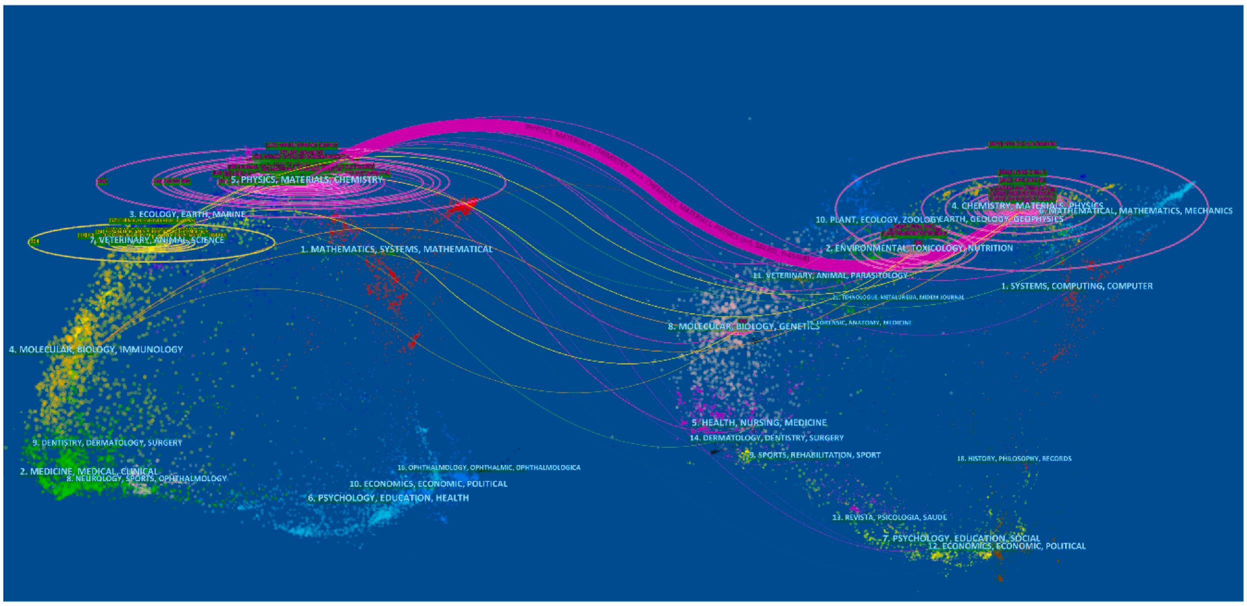


Fig. 6. Venation diagram of article citing relationship.

Table 4
Top 10 journals in terms of article production and citation volume from 2007 to 2021.

TOP10	TC	TP	Centrality	IF	institution	Year
1	9301	70	0.38	24.319	Applied Catalysis B-Environmental	2007
2	4425	35	0.22	4.177	Journal of Physical Chemistry C	2007
3	4386	97	0.06	7.392	Applied Surface Science	2009
4	3794	54	0.03	16.744	Chemical Engineering Journal	2010
5	3156	23	0.06	10.383	ACS Applied Materials & Interfaces	2011
6	2330	28	0.06	14.224	Journal of Hazardous Materials	2009
7	2273	78	0.03	4.036	Rsc Advances	2013
8	2054	54	0.09	9.965	Journal of Colloid and Interface Science	2010
9	1691	20	0.09	14.511	Journal of Materials Chemistry A	2013
10	1572	54	0.00	6.371	Journal of Alloys and Compounds	2007

set) and GCS (the total number of citations in all databases). The higher the LGS was, the higher the importance of this article in the field of Bi_2WO_6-based photocatalytic nanomaterials. The higher the GCS was, the more frequently the article was cited in other fields and the more interdisciplinary. Table 5 lists the top 10 most-cited articles in the field of photocatalysis of Bi2WO6-based nanomaterials over the past 15 years.

From Table 5, the highest cited article from 2007 to 2022 was《Synthesis of Bi_2WO_6 Nanoplate Built Hierarchical Near like Structures with Visible Light Induced Photocatalytic Activity》 published by Wu in 2007. It was shown here that changing the morphology and size of the photocatalyst is an effective means for improving photocatalytic activity [53]. Wu et al. have modified Bi_2WO_6 with polyvinylpyrrolidone (PVP) to prepare layered nested Bi_2WO_6 nanoplates and also analyzed the synthesis steps. They confirmed that PVP crystals play an important role in the formation of Bi_2WO_6 nanostructures due to its anisotropy and surface inhibitor function, which provides more ideas for solving the relationship between structural control and performance optimization of nanomaterials. At the same time, this study discussed the electrochemical performance of Bi_2WO_6 nanomaterials as lithium ion battery electrodes for the first time, providing more choices for candidate materials of lithium ion battery electrodes in the future [54]. Shang et al. have shown that Bi_2WO_6 nanoparticles can be minimized by ammonium bismuth citrate to increase their surface active sites, which greatly improves catalyst performance. However, the size of Bi_2WO_6-based nanomaterials is too small to be recycled in practical applications. Therefore, Shang et al. [55] in 2009 have successfully prepared Bi_2WO_6 nanocages in Ethylene Glycol by a reflux process using colloidal carbon spheres as templates. Bi_2WO_6 nanocages have been composed of 50–80 nanoparticles with a single size of 1 nm and naturally settled within 15 min after reaction. On the premise of ensuring photocatalytic efficiency, this is also convenient for the

Table 5
Analysis of historical high citations in the field of photocatalysis of Bi_2WO_6 based nanomaterials.

Year	Author	Title	Research content	LCS	GCS
2007	Ju Wu	Synthesis of Bi_2WO_6 Nanoplate-Built Hierarchical Nest-like Structures with Visible-Light-Induced Photocatalytic Activity	Bi_2WO_6 nano plate with layered nest structure was synthesized by using polyvinylpyrrolidone, and its electrochemical performance as lithium ion battery electrode was discussed for the first time	214	359
2014	Nan Zhang	Nanochemistry-derived Bi2WO6 nanostructures: towards production of sustainable chemicals and fuels induced by visible light	In this paper, the application of Bi2WO6-based nanomaterials as catalysts and fuels was studied from the perspective of nanochemistry	140	304
2013	Jian Tian	A Bi2WO6-Based Hybrid Photocatalyst with Broad Spectrum Photocatalytic Properties under UV, Visible, and Near-Infrared Irradiation	Bi_2WO_6 nano sheets were assembled on TiO_2 nanobelts to construct a Bi_2WO_6 -TiO_2 nanobelt heterostructure, which enhanced the utilization efficiency of visible light.	132	478
2008	Meng Shang	Bi2WO6 nanocrystals with high photocatalytic activities under visible light	Minimize Bi_2WO_6 nanoparticles by ammonium bismuth citrate to increase their surface active sites	125	212
2008	QiXiao	Photocatalytic degradation of methylene blue over Co3O4/Bi2WO6 composite under visible light irradiation	Co_3O_4/Bi_2WO_6 p-n junction heterostructures were prepared by immersion method, which enhanced the absorption of visible light and suppressed the recombination of photogenerated electrons and holes	116	223
2009	Li-WuZhang	Synthesis of Porous Bi2WO6 Thin Films as Efficient Visible-Light-Active Photocatalysts	Bi_2WO_6 ordered porous membrane with open pores was prepared, which has high photocatalytic activity and photocurrent coverage efficiency.	115	301
2009	Meng Shang	New Bi2WO6 Nanocages with High Visible-Light-Driven Photocatalytic Activities Prepared in Refluxing EG	Bi_2WO_6 nanocages were successfully prepared in EG by reflux process using colloidal carbon spheres as templates.	115	204
2008	Ling Wu	Rapid preparation of Bi2WO6 photocatalyst with nanosheet morphology via microwave-assisted solvothermal synthesis	According to the modification of Bi_2WO6 surface morphology, Bi_2WO_6 nanocrystals were prepared by microwave heating	111	175
2011	Ming Ge	Bi2O3- Bi2WO6 Composite Microspheres: Hydrothermal Synthesis and Photocatalytic Performances	Under the action of surfactant cetyltrimethylammonium bromide (CTAB), chrysanthemum like Bi_2O_3–Bi_2WO_6 composite microspheres were prepared	109	213
2009	Jia Ren	Enhanced photocatalytic activity of Bi2WO6 loaded with Ag nanoparticles under visible light irradiation	The photocatalytic properties of Bi_2WO_6 nanomaterials were modified by the precious metal (Ag) deposition method using vinyl alcohol.	106	208

separation and recycling of materials. In the same year, Ren et al. [56] have proposed to deposit precious metal Ag on Bi_2WO_6 under the action of vinyl alcohol, such that precious metals and semiconductors can be synthesized into composite materials. Their results show that, compared with single Bi_2WO_6, capabilities from the fire-extinguishing ability of composite materials with precious metals to antibacterial activity against gram negative bacteria, Escherichia coli, Staphylococcus epidermidis, and gram positive bactria can be greatly enhanced.

3.4.2. Co-citation clusters

The above 10 highly cited papers have laid a solid foundation for researchers in the field of Bi_2WO_6-based nanomaterials modification. In order to explore the main research topics and development trend, the literature co-citation network is analyzed. The log-likelihood ratio (LLR) function was used to identify the cluster labels, and the cluster was divided into 10 co-citation clusters.

Fig. 7 shows a timeline diagram of the co-referenced document cluster. The clustering of these keywords was divided into 10 subclusters, including nanoparticle, photocatalytic activity, fabrication, oxide, nanosize Bi_2WO_6, TiO_2, visible light, reduction, and mechanism. Then, the timeline of keywords was examined in Fig. 7, with subclusters generated at the end of the cluster timeline in Fig. 6 representing the frontier topics in each cluster corresponding to keyword clustering in Fig. 6. The node of the keyword timeline represented the time when the keyword first appeared in 2007–2022 and the connection represented that the same keyword appeared in different years and articles, which yielded the research of the two related. There were many jump clusters, such as the nanoparticle in #0 jumped to bismuth tungstate in #5 and fabrication in #2. At the same time, there were many cross-year situations. For example, the nanoparticle in #0 extended from 2007 to 2018, which meant that the research related to nanoparticle had been extended from 2007 to 2018.

Changes in the number of keywords over the years can well reflect the current research focus in this field. Examination of the top 10 popular keywords in different stages from 2007 to 2022 ranked them according to their frequency of occurrence (Table 6). In general, "degradation," "Bi_2WO_6," and "performance" appeared most frequently, indicating that the most important thing for Bi_2WO_6-based photocatalytic nanomaterials was to improve their photocatalytic performance to improve pollutant degradation efficiency. From the word "water" in the 5th place, Bi_2WO_6-based photocatalytic nanomaterials were seen to be mainly used to treat organic pollutants in the water environment. It is interesting to note that the word "heterojunction" in the 8th place appeared at a frequency of 1 in 2007–2011. The reason for this phenomenon might have been because researchers called it "composite" before 2011 and had not made an in-depth study of composite heterostructure. Similarly, the 10th-ranked "nanosheets" also experienced a similar situation. According to "nanoparticles" ranking 7th, although both of them are nanostructures, "nanoparticles" also included different forms, such as microspheres, rods, or sheets, and the morphology and performance of nanomaterials were inextricably linked [57,58]. Therefore, with in-depth research, researchers have invested much effort to obtaining ideal morphology and good performance in the preparation and synthesis of nanomaterials with different morphologies. The research on "nanosheets" also increased over time from 0.004 to 82.5% in 2017–2022.

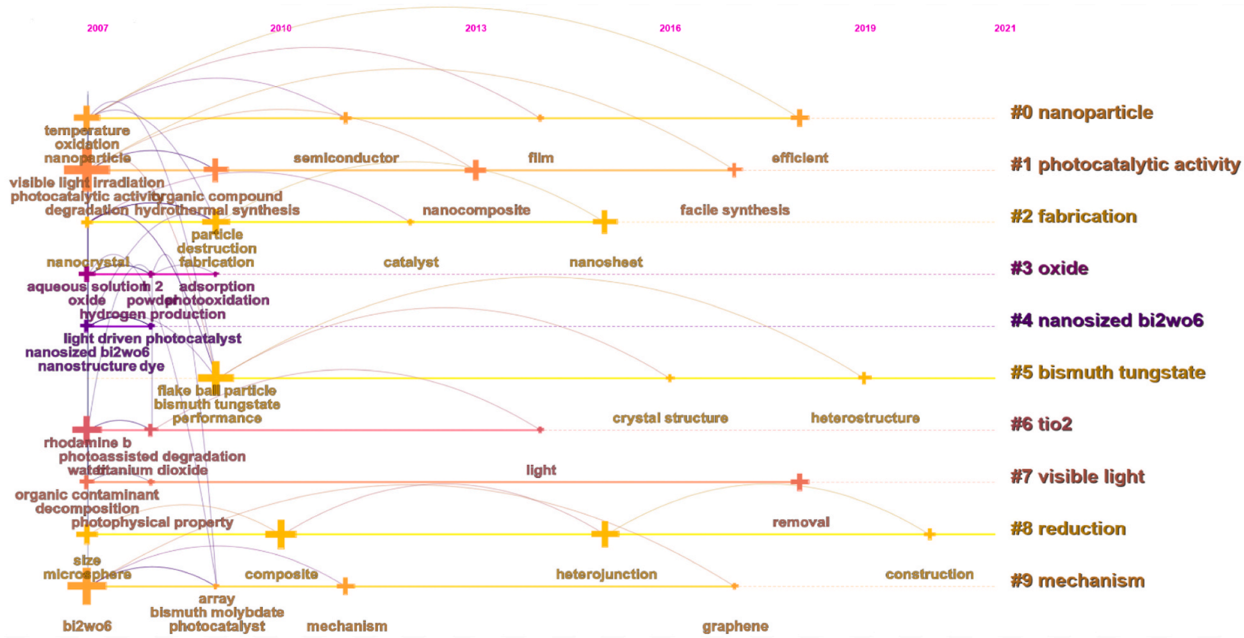


Fig. 7. Sequence diagram of ten clusters of keywords, showing the emergence and alternation of research hotspots.

Table 6
Growth trend of top 10 popular keywords in the field of Bi_2WO_6-based photocatalytic nanomaterials from 2007 to 2022.

TOP10	Keywords	TP	2007–2011 R (%)	2012–2016 R (%)	2017–2022 R (%)
1	degradation	833	65 (7.81%)	300 (36.01%)	468 (56.18%)
2	Bi_2WO_6	621	58 (9.34%)	189 (30.43%)	374 (60.23%)
3	performance	484	6 (1.24%)	128 (26.44%)	350 (72.32%)
4	TiO_2	323	51 (15.79%)	136 (42.11%)	136 (42.10%)
5	water	320	40 (12.50%)	116 (36.25%)	164 (51.25%)
6	fabrication	283	13 (4.59%)	62 (21.91%)	208 (73.50%)
7	nanoparticles	265	29 (10.94%)	75 (28.30%)	161 (60.76%)
8	heterojunction	250	1 (0.004%)	41 (16.80%)	208 (83.20%)
9	composite	240	12 (5.00%)	65 (27.10%)	163 (67.90%)
10	nanosheets	240	2 (0.01%)	40 (17.50%)	196 (82.50%)

3.5. *Research hotspots*

3.5.1. *Co-occurrence of the keywords*

Keywords are words or phrases indexed to understand a particular field. Keyword cluster analysis was used to get a quick overview of research trends in Bi_2WO_6-based photocatalytic materials in the field of water treatment. In this paper, the 2064 articles obtained were analyzed for keywords by the Bibliometrix software package to obtain the following results (Fig. 8): a total of four clusters were formed.

Clusters #1 is oxidation, mainly indicating that oxidation reactions are an important factor in the application of Bi_2WO_6 in the aqueous environment. The oxidative degradation of pollutants in water depends mainly on the oxidation capacity of photocatalysts. Therefore, how to effectively improve the oxidation performance of Bi_2WO_6-based photocatalytic materials has sparked the attention of many scholars.The structure of Bi_2WO_6 has been found to belong to layered oxides of orthogonal crystal phase, which is composed of $(Bi_2O_2)^{2+}$ and $(WO_4)^{2-}$ layers. The special layered structure makes Bi_2WO_6 a metal oxide with a narrow band gap and high valence band [59]. Lei Ge et al. synthesized a novel visible light induced $g\text{-}C_3N_4/Bi_2WO_6$ composite photocatalyst by introducing polymerized $g\text{-}C_3N_4$. Through DRS, it was obvious that $g\text{-}C_3N_4/Bi_2WO_6$ samples had redshift and strong absorption in the visible light region. The photocatalytic oxidation ability of the composite material was verified, and it was proved that the composite photocatalyst showed good photocatalytic performance in the degradation of methyl orange. Through characterization, it was determined that the coordination between $g\text{-}C_3N_4$ and Bi_2WO_6 improved the separation of photogenerated carriers, and its unique heterojunction structure also enhanced its photocatalytic performance [60]. Zhang L et al. used AgBr–Ag– Bi_2WO_6 nanojunction system as catalyst for effective photocatalytic disinfection of E. coli K-12. cfu mL (-1) E. coli K-12 can be completely inactivated within 15 molecules, and the composite catalyst material shows excellent performance in comparison with the catalyst types of the same period. By exploring the mechanism, it was found that the dispersive hydroxyl radicals produced by oxidation and reduction pathways play an important role in

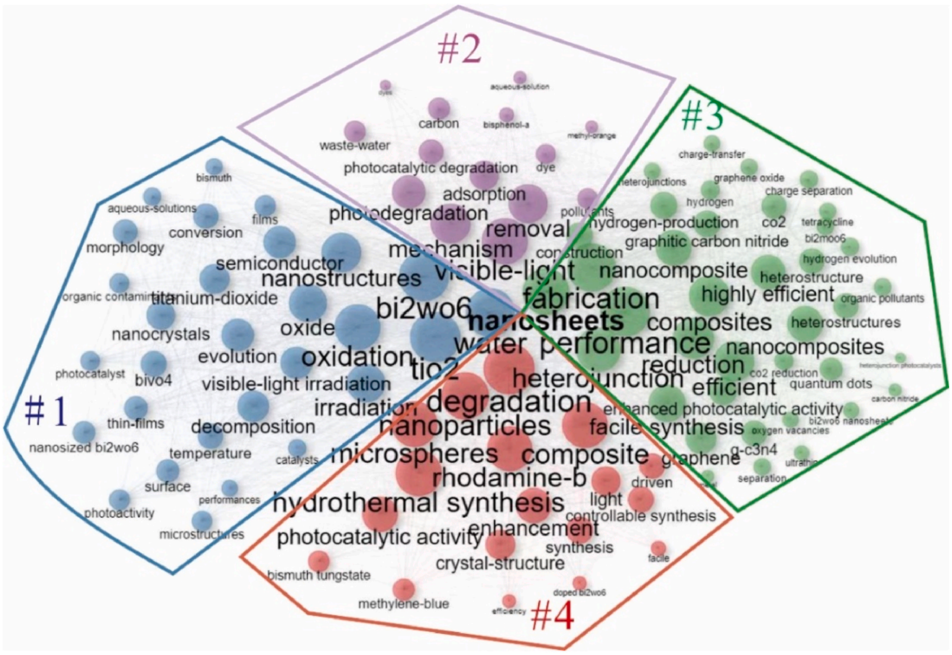


Fig. 8. Keyword clusters for Bi_2WO_6-based photocatalytic nanomaterials.

photocatalytic disinfection. This study provides a potentially effective photocatalyst to sterilize bacterial cells and even destroy biofilms that provide shelter and substrate for microorganisms and resist disinfection. It provides a new research direction for researchers [61]. Li BS et al. prepared a highly efficient $Bi_2Fe_4O_9/Bi_2WO_6$ photocatalytic material by hydrothermal method, and the degradation rate of Rhodamine B (RhB) was 100% within 90 min. Through further study, it is found that effective photoinduced carrier separation, wider light absorption range, high oxidation capacity of holes and high reduction capacity of electrons are the reasons for the improvement of catalytic activity after the formation of Z-scheme system. The presence of major free radicals, such as holes (h^+), hydroxyl radicals (OH) and superoxide radicals, was also found in the system. The catalytic performance of the composite did not decrease significantly after 5 cycles, which also proved that the composite photocatalytic materials with Z-type heterojunctions have great prospects in the environment [62]. However, due to its low conduction band energy level and poor absorption of visible light, Bi_2WO_6 still needs to be investigated in more depth in order to improve its photocatalytic performance.

Clusters #3 are nanocomposites, Clusters # 4 is a heterogeneous, mainly illustrating that combining Bi_2WO_6 with other elements or ions to form nanocomposites is one way to effectively improve photocatalytic performance. In the study of degradation performance of nanocomposites, researchers have realized composite nanomaterials by doping different nonmetallic elements or metal ions. When atoms in Bi_2WO_6 are replaced by other different ions or when different atoms are introduced, charge compensation effects may occur, changing the crystal structure or charge composition pattern of Bi_2WO_6 and further altering its physicochemical properties. Zhang, N et al. prepared Bi_2WO_6 materials with superstructure form through nanochemistry, resulting in better electron-hole separation and higher photoactivity. The recent results, combined with the versatile photochemistry of this readily available semiconductor, suggest that future practical applications of nanochemically derived Bi_2WO_6 nanostructures are possible. We describe advances in this important area of chemical research from the perspective of nanochemistry and identify opportunities for further progress [63].Song et al. [64] have introduced Br into Bi_2WO_6 lattices by a microwave hydrothermal method for preparing three-dimensional layered Br/Bi_2WO_6 nanoparticles. Their results show that Br doping reduces the recombination rate of photogenerated electrons and holes in these semiconductor materials and achieve efficient degradation of RhB. Ma, D et al. prepared an efficient visible-driven Z-scheme $g\text{-}C_3N_4/RGO/Bi_2WO_6$ composite by hydrothermal method. The degradation experiment of trichlorophenol was carried out under visible light, and it was found that photogenerated electrons and holes had strong reducing and oxidizing abilities, respectively. The main reason for this structure was that Z-scheme retained electrons with high reducing ability in the conduction band (CB) of $g\text{-}C_3N_4$. The holes with high oxidation capacity are retained in the valence band (VB) of Bi_2WO_6. The photogenerated holes of Bi_2WO_6 are the main active substances in the oxidative degradation of trichlorophenol, and the photogenerated electrons of $g\text{-}C_3N_4$ are the main active substances in TCP dichlorination [65]. Cao, SW et al. prepared a kind of MXenes 2D Ti_3C_2 nanosheet by ultrasonic stripping and etching of Ti_3AlC_2, and superimposed Bi_2WO_6 ultra-thin nanosheet by the way of original growth, and successfully prepared ultra-thin Ti_3C_2/Bi_2WO_6 nanosheet by observation, and realized 2D/2D heterojunction. The composite material has shorter charge transport distance and relatively large contact area, which enables efficient charge transfer capability. In the adsorption experiment of CO_2, it is proved that it has good adsorption performance, which is attributed to the good specific surface area and pore structure of the hybrid material. In the experiment of the total yield of CH_4 and CH_3OH, it is proved that the material has better catalytic performance than the original Bi_2WO_6 ultra-thin nanosheets, and the heterogeneous structure of 2D/2D is the main reason for its better catalytic performance. This study provides a new scheme for constructing 2D/2D photocatalytic systems and proves that Ti_3C_2 is a promising and inexpensive cocatalyst. Through the study, it is found that the combination of heterojunction structure and nanosheet material can improve the defects of Bi_2WO_6 material more effectively, so that Bi_2WO_6 has better band gap width and good light response intensity [66].

In the study of semiconductor catalyst heterostructure, researchers have further studied the electron transfer path in heterostructures on the basis of nanocomposite materials. These heterostructures have been divided into three types, including type I heterostructures, type II heterostructures, and direct Z-scheme heterostructures [67,68]. Type I heterostructures are mainly typified by the transfer of electrons and holes from one semiconductor to another semiconductor, but such structures is very unfavorable for reducing the recombination of electron holes. Type II heterostructures involved the transfer of electrons and holes to different semiconductors, such that, being at the two ends of the heterojunction, the electron-hole recombination rate is reduced. However, photogenerated electrons and holes flow to the conduction and valence bands with lower potential, which weaken the oxidation exchange ability of the catalyst. In contrast to type I and II heterostructures, direct Z-scheme heterostructures do not exist in physical contact, but rely on the charge of redox electron mediator for transport. Due to the potential difference between the two semiconductors, the electron holes in the valence and conduction bands with lower potential are combined and eliminated. Thus, the valence and conduction bands with higher potential are retained, which effectively improves the redox capacity of the catalyst [69].

Clusters #2 is adsorption-photocatalysis, suggesting that a combination of methods is an effective way to address low photocatalytic performance. At present, adsorption and photocatalysis are considered as two effective methods for treating water pollution. In the study of adsorption/photocatalysis synergy, our group has prepared a series of modified Bi_2WO_6 materials by adding different dispersants and found that the adsorption and photocatalytic performance of these modified Bi_2WO_6 products were greatly improved [70]. Moreover, pollutants were adsorbed on the catalyst surface through the adsorbability of the materials, thus enhancing the synergy of adsorption and photocatalysis and improving the removal efficiency of tetracycline. Huang, HW et al. prepared Bi_2WO_6 materials with three-dimensional layered structure by means of auxiliary assembly, in which SDS with shorter chains was less effective than SDBS. Due to the full exposure of O atoms on the surface, the monolayer 3D Bi_2WO_6 shows strong selective adsorption of various forms of organic dyes with different charges. The single-layer 3D Bi_2WO_6 greatly improves the photodegradation activity, and the point electrochemical characterization proves that the significant improvement of carrier density and charge separation efficiency is the reason for the enhanced photocatalytic performance. The research not only provides insights for designing single-layer assembled 3D layered structures, but also provides multifunctional materials for environmental and energy applications [71]. Yue, LF et al.

synthesized three-dimensional mesoporous multi-wall carbon nanotube- Bi_2WO_6 (MWNTs- Bi_2WO_6) composite photocatalyst materials by hydrothermal method, and applied them to the degradation of tetracycline in water. The addition of MWNTs promoted the transfer of photogenerated electrons, and enhanced the separation of photogenerated holes and electron pairs. The composite material also showed better light absorption performance in the visible region. The large surface area of MWNTs and the electron coupling between MWNTS and pollutants promote the adsorption of tetracycline on the surface of the composite photocatalyst. The adsorbed tetracycline can also be degraded with the extension of light time [72]. Through the summary of the above literature, it is found that the research on the adsorption performance of photocatalyst materials has also attracted extensive attention from scholars in recent years, and the composite with other materials has improved both the adsorption performance and the photocatalytic ability of materials.

Adsorption-photocatalytic collaboration has been a new topic in recent years, with composite catalysts prepared by combining carbon materials with Bi_2WO_6 attracting much attention for improving the performance of Bi_2WO_6-based photocatalytic nanomaterials [73,74]. Because of its large pore structure, carbon materials have often been used to adsorb organic pollutants in the environment. Through literature review, the aromatic ring structure and surface functional groups of most carbon materials have been found to have the ability to promote electron transfer in photocatalysts [75,76]. If carbon materials are combined with Bi_2WO_6, pollutants can be enriched on catalyst surfaces by adsorption onto carbon materials, thus enhancing the photocatalytic performance of Bi_2WO_6-based photocatalytic nanomaterials. However, there have been few studies on the combination of adsorption and photocatalysis to date, which can be a theme explored in the future.

3.5.2. *Burst keywords*

Highlighted words are used to study the frequency of keyword citations based on time trends, so as to further analyze research trends and hotspots [77,78]. The top 10 the strongest citation burst words in the field of Bi_2WO_6-based photocatalytic nanomaterials from 2007 to 2022 were obtained by CiteSpace visualization software (Table 7). The strength of highlighted words represented the frequency of keywords being cited in that year. In accordance with Table 6，the stage can be divided into two categories. First stage (2007–2013)： In this stage, researchers rapidly started to investigate the modification of Bi_2WO_6-based photocatalytic materials, resulting in a surge in the citation of keywords such as “decomposition”, “nanosized Bi_2WO_6 ″, “organic contaminant” and other keywords have been cited extensively. A series of studies have been carried out to modify the nanomorphology of Bi_2WO_6 for the purpose of oxidative degradation of organic contaminants. Bi2WO6 was synthesized by hydrothermal method, and Rhodamine B was degraded by micro-blog-assisted photocatalysis. The experimental results showed that the removal rate of pollutants could reach 94% within 60 min [79]. At this stage, the research on basic modification of materials to improve the removal ability of pollutants is still in a relatively common development stage, and the exploration of Bi_2WO_6 photocatalytic materials needs to be further studied.

This stage is more focused on the morphological control of catalysts and is a basic research phase. Second stage (201–2023):This stage focuses on the modification of the structure mechanism of Bi_2WO_6-based photocatalytic materials. Construction, oxygen vacancy are the key words that have been cited in the strongest explosion in recent years, representing the research frontier and future development trend of Bi_2WO_6-based photocatalytic materials. Increased frequency of references to “construct” and “oxygen vacancy”, the degradation of methylene blue by $BiPO_4$, a photocatalyst with non-metallic acid structure prepared by Pan, CS et al., using hydrothermal synthesis, is twice that of TiO_2. Among them, the high position of valence band and the efficient separation of electron holes make it the main reason for the degradation of pollutants. The material has excellent photocatalytic activity, and its unique composition can be extended to the oxidation and catalytic synthesis of other inorganic nonmetallic salts for the purification of organic pollutants in the water environment [80]. Huo, WC et al. successfully prepared Bi_2WO_6 (BWO) with gradient oxygen vacancy concentration, and demonstrated excellent performance on NO oxidation through experiments. Through the formation of oxygen vacancy defects, the band structure and chemical state of BWO are regulated, and the carrier separation efficiency is improved. A series of characterization has proved that the formation of oxygen vacancy defects plays an important role in the modification of photocatalyst materials [81]. Huang et al. [82] have introduced oxygen vacancies and metal Bi into Bi_2WO_6 nanostructures. Their results show that the addition of oxygen vacancies and metal Bi produces more active species, including singlet oxygen ($^1O_2$) in the process of photocatalytic reaction. This greatly improves photocatalytic performance and enhances anti-interference in aqueous solution, yielding photocatalytic reactions more stable.

The analysis of the above literature shows that this stage focuses more on structural modification and in-depth exploration of catalyst band structure, and both modification methods and theoretical perspectives are highly innovative.

To sum up, the regulation of Bi_2WO_6 nanostructures was learned to still be a research hotspot in this field, based on the highlighted words shown by the data at home and abroad. Exploring better regulation methods of Bi_2WO_6 nanostructures is the direction needed to pursue in future research efforts.

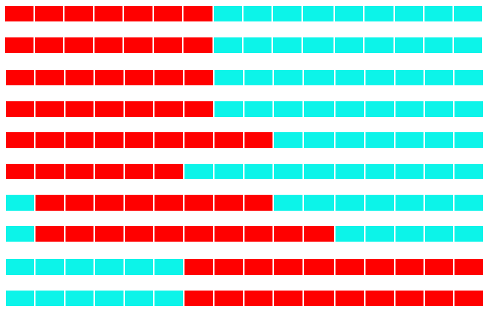
4. Conclusions

This study conducted the bibliometric analysis of 1975 articles published in the field of Bi_2WO_6-based photocatalysts from 2007 to 2022. By using the Bibliometrix software package and CiteSpace software, some basic characteristics of the collected data were analyzed in terms of annual publications, publication category, and publication sources. The articles in the Bi_2WO_6-based nanomaterial field were found to have the following characteristics.

The research on Bi_2WO_6-based photocatalysts has witnessed substantial growth over the past 15 years, evident from the escalating number of publications in this field. China has emerged as a prominent contributor, assuming a crucial role and engaging in extensive collaborations with other nations. This has facilitated international exchange, knowledge transfer, and overall advancements within

Table 7
Top 10 keywords with strongest citation bursts.

Keywords	Year	Strength	Begin	End	2007-2022
decomposition	2007	22.57	2007	2013	
nanosized Bi_2WO_6	2007	17.93	2007	2013	
organic contaminant	2007	15.84	2007	2013	
irradiation	2007	15.52	2007	2013	
visible light irradiation	2007	11.27	2007	2017	
aqueous solution	2007	9.82	2007	2012	
titanium dioxide	2007	16.9	2008	2015	
TiO_2	2007	10.39	2008	2014	
construction	2007	10.96	2013	2022	
oxygen vacancy	2007	10.56	2013	2022	



the field. Notably, the journal "Applied Catalysis B-Environmental" (H = 56, IF = 24.319) holds the highest influence when considering the impact of articles. This underscores the significant role of Bi_2WO_6-based photocatalysts in surface science, catalysis, and chemical engineering, given their interdisciplinary nature. Furthermore, the investigation of the synergistic effect of photocatalysis and adsorption has emerged as a key research area with a focus on enhancing catalytic efficiency. By combining Bi_2WO_6 nanomaterials with adsorbent materials, it becomes feasible to adsorb organic pollutants onto the catalyst's surface, thereby increasing the reaction surface area and facilitating effective pollutant removal. However, it is important to note that the application of this approach in current studies remains relatively limited. Therefore, future research should aim to further explore and provide more potential solutions for enhancing the catalytic efficiency of photocatalysts.

Ethical statement

No ethical approval was required as this study did not involve human participants or laboratory animals.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

CRediT authorship contribution statement

Sen Li: Writing – original draft. **Yiling Liu:** Writing – review & editing. **Yanbo Xiao:** Data curation. **Haiyan Ma:** Investigation. **Jing Duan:** Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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