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RECENT PROGRESS IN THE UTILIZATION OF SILVER NANOPARTICLE AND ITS DERIVATIVES AS PHOTOCATALYST: A MINI BIBLIOMETRIC STUDY

The narrow bandgaps of silver nanostructure and its derivatives make them photocatalytic-efficient. This bibliometric examines silver nanoparticle research in photocatalysis to identify its growth, research gap, and trends. The 1,941 Web of Science Core Collection publications from 2018 to 2023 were used as research data. The search used Publish or Perish, and the investigation was established on topic area with titles, abstracts, keywords, and terms co-occurrence in the study of silver-based photocatalyst. The visualisation was done with VOSviewer. The number of papers on silver nanoparticles and their derivatives as photocatalysts fluctuated, peaking in 2019. The publications focused on visible-light-irradiated photocatalysts. These findings also revealed a research gap that can be filled by studying silver derivatives including silver chloride, silver oxide, silver sulfide, and silver iodide. This bibliometric study should help researchers examine silver nanoparticles in photocatalysis.

Keyword: Bibliometric study; VOSviewer; silver nanoparticles; photocatalysis

1. Introduction

Photocatalysis is described as the simultaneous use of light and a catalyst to speed up a chemical transformation that occurs on the catalyst's surface. This catalyst also called a photocatalyst. When subjected to light energy, the photocatalyst absorbs photons and converts them into electron-hole (e^-/h^+) pairs. In response to the presence of these two charges, water or oxygen molecules will undergo a chemical reaction, producing reactive radicals such as hydroxyl radicals (•OH) and superoxide radicals (O_2^-), which help to oxidize or decrease the harmful chemicals in wastewater [1]. Since the last few decades, photocatalysis has emerged as one of the most outstanding techniques based on green environment technology, and it is also extensively employed as a cutting-edge solution for dyes wastewater treatment from the aquatic environment along with the rapid expanding industrial world, particularly the textile industry [2].

It has been discovered that many photocatalysts belong to the class of metal semiconductors, which are able to react when exposed to light wavelengths especially the ultraviolet (UV), visible (Vis), and near-infrared (UV-Vis-NIR) spectrum. In the past decade, the two well-known UV-activated photocatalysts namely titanium dioxide (TiO_2) [3,4] and zinc oxide (ZnO) [5,6], have been widely studied due to their adequate ability to degrade organic pollutants, wide bandgap, and rapid generation of electron-hole pairs by photoexcitation [7,8]. However, UV is only about 3% available in nature [9], whereas visible light accounts for 42% of solar energy [10] and near-infrared is 50% [1]. Since the sunlight is a renewable energy source, the inability to activate those photocatalysts under solar irradiation reduces their environmental benefit. Furthermore, photocatalysts are gaining popularity as scientists investigate their potential use in converting harmful compounds into less harmful or more environmental friendly products when subjected to sun irradiation that encompasses the entire spectrum of ultraviolet, visible, and near infrared (UV-VIS-NIR) light [11-14].

In the beginning of photocatalysis's development, each photodegradation was carried out by photocatalyst semiconductor material. However, the use of a single semiconductor material as a photocatalyst seems to have a negative effect on the photocatalytic activity due to its poor charge transfer efficiency, quick recombination rate of the photogenerated electron-hole pairs, and reduced recyclability [15-18]. The rapid recombination of electron-hole pairs reduces the yields of the reactive radical's species (•OH & O_2^-) and, as a result, restricted the practical application of this feature [9,19].

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To date, considerable efforts have been made in the field of UV-Visible-NIR photocatalysis to overcome the drawbacks and create a recyclable photocatalyst with fast charge conversion and low electron-hole recombination rate [9]. The use of hybrid multiple materials and cocatalysts are predicted to be the best solution to modify the initial properties of the photocatalysts for creating renewable materials with preferred properties and best photocatalytic performance under solar irradiation [20-22]. Composite photocatalyst, heterojunction photocatalyst, bio-templated photocatalyst, thin film photocatalyst and other types of photocatalyst are examples of the multiple materials implementations. Noble metal such as silver, gold and platinum are the most favourable cocatalyst utilized within the photocatalysis due to its great photocatalytic efficiency under the sunlight [2,23,24]. Since silver is less expensive and relatively stable in comparison with other noble metals, silver nanoparticle and its derivatives are frequently utilised as a photocatalyst [2]. Silver nanoparticles can boost photocatalytic efficacy by capturing electrons, and facilitating the separation of photon-generated electrons and holes [25].

The entanglement of silver nanoparticle and its derivates such as silver sulphide (Ag_2S), silver chloride (AgCl), silver phosphate (Ag_3PO_4), silver bromide (AgBr), etc., in the photocatalytic degradation process is well known in literatures [1,28-31]. In previous studies, it was found that the incorporation of the Ag_2S powder into the cellulose film could maximize the degradation rate of methylene blue up to 100% within 120 minutes under solar irradiation. The Ag_2S powder worked as photocatalyst that absorbs the sunlight and boost the charge separation. Meanwhile, cellulose film employed as a host during photodegradation which supressed the recombination rate of charge carriers [1]. Afterwards, research by Chen et al. suggests that a composite of silver sulphide-silver-zinc-cadmium selenide (Ag_2S-Ag-Zn-CdS) has resulted in a hybrid photocatalyst with high charge transfer efficiency and longer carrier life; this would account for the best Rhodamine B degradation efficiency of 83% in 40 minutes, with notable stability and repeatability over at least four cycles [27]. The same result was also exhibited by Li et. al., which demonstrated a great enhancement of photocatalytic efficiency under visible light that was established by the heterojunction structure of tri-tungsten (iv) oxide (WO_3) film and Ag/AgCl nanoparticles [28]. Aritonang et. al. in their study indicated that bio-templated Ag-ZnO nanoparticles in bacterial cellulose was a promising candidate for UV-Vis responsive photocatalyst and offering its potential as recyclable photocatalyst [29]. Other than for photocatalytic applications, silver nanoparticles and its derivatives also have influence on heat transfer fluid applications since Brownian motion of nanoparticles helps to prevent their agglomeration or settling within the fluid, ensuring that they remain well-dispersed, reducing the thermal resistance and maintain their heat transfer-enhancing properties over time [30]. Silver nanoparticles also can be used in tuning the thermal conductivity of composite structures. For example, the thermal conductivity of carbon nanotubes reinforced composites can be tuned by adjusting the concentration and distribution of silver nanoparticles within the composite matrix. By varying the loading of silver nanoparticles, researchers can optimize the thermal properties of the composite for specific applications, balancing factors such as thermal conductivity, mechanical strength, and cost-effectiveness [31].

So far, some published works have carried out an in-depth analysis of the research on the silver nanoparticles-derived photocatalyst. Because of the abundance of scientific writing and other documentation on this topic, a vast archive of information is now available. Hence, data analysis in terms of publication tracking, is impossible without the use of modern tools and techniques [32]. In this study, we employed the bibliometrics and data mining to assess scientific papers indexed in the Web of Science (WoS) core collection. To the best of our knowledge, this is the first bibliometric study to examine trends in research on silver nanoparticle-based photocatalysts. The findings of this study can assist researchers to comprehend research trends, observe research hotspots, track the research gap, and explore future research directions. Bibliometric analysis is the process of attempting to quantitatively evaluate the academic quality of publications or writers using statistical approaches such as the number of times their work has been cited [33]. Furthermore, for bibliometric analysis, this study utilizes Publish or Perish (PoP) and VOSviewer. The VOSviewer software is used to establish and display bibliometric networks. Journals, researchers, and individual articles can all be connected in a network that is built on the foundation of authorship, co-authorship, citation, co-citation, and bibliographic coupling. In addition, VOSviewer provides a text mining feature that could be utilized to build and visualize co-occurrence networks of relevant terms retrieved from a body of scientific publications [34].

2. Data and methods

2.1. Data collection

To ensure the reliability, accuracy, and credibility of the relevant literatures, a reference manager application called Publish or Perish was used to harvest the publication data from the Web of Science (WoS) Core Collection, specifically articles about the use of silver nanoparticles and their derivatives in photocatalysis. The relevant literatures were collected by retrieving titles and abstracts, with the use of the Boolean search operator to narrow down the amount of data collected and to specify the subject area. The framework of the process in harvesting data in the recent study is displayed in Fig. 1. The search returned 1,941 documents from the WoS database. Then, the data was put together in plain text (.txt) format with the cited references.

2.2. Bibliometric analysis method

After the data was compiled into plain text (.txt) format, they were imported into the VOSviewer (version 1.6.18) mapping tool for conducting a visualization analysis at the acquired data. The aim of this analysis was to determine the publication

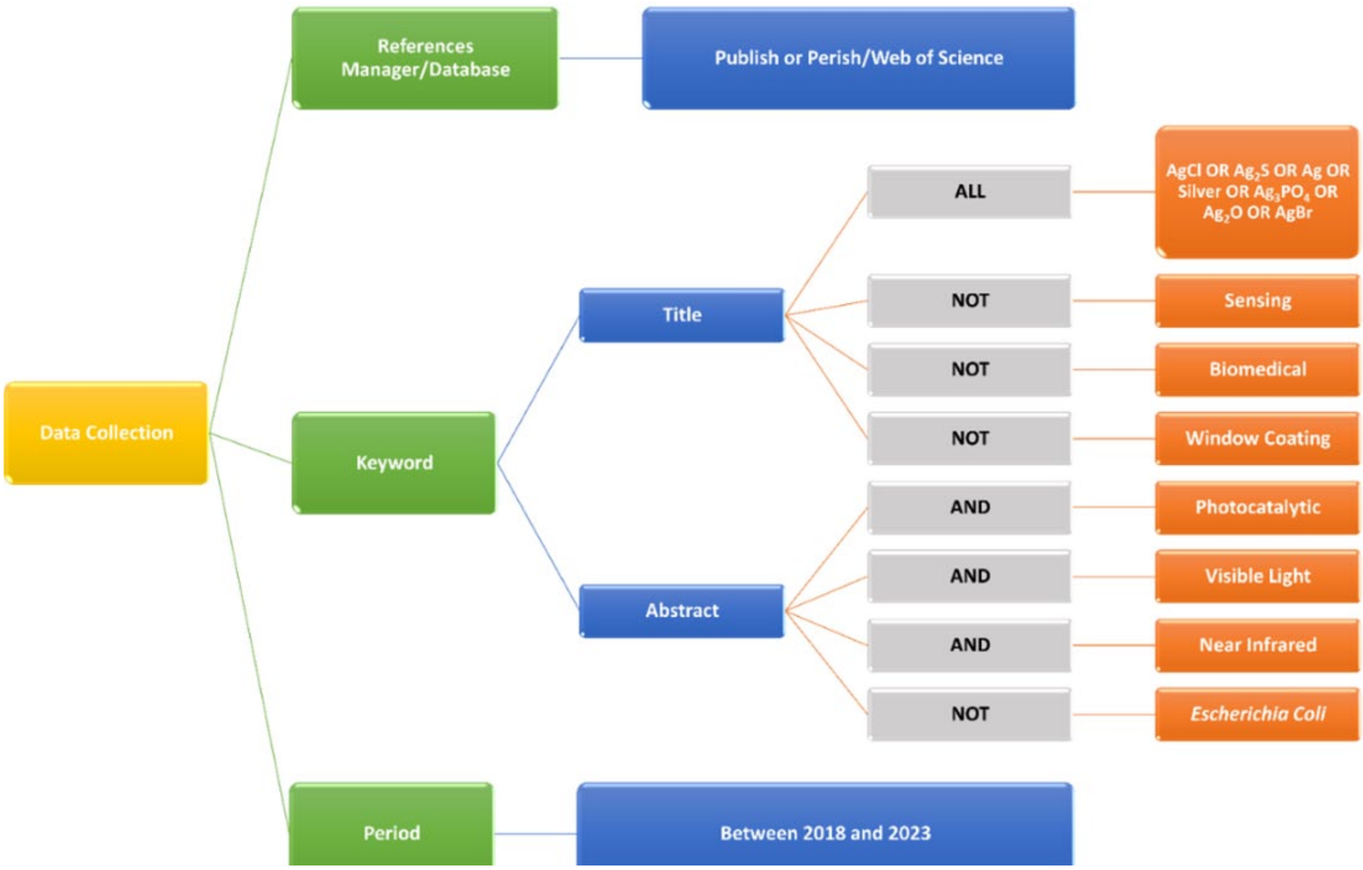

Fig. 1. Data collection framework

volume, authors relationships, research hotspots, co-occurrence patterns within the data, which were subsequently represented in an interconnected data map. Afterwards, at “data source” section, the data was read from the bibliographic database file (Web of Science). The bibliometric analysis was then continued by selecting the type of analysis and employing a full counting method. Finally, VOSviewer will automatically generate the scientific map following the setting that is input into the software. The produced scientific map has the capability to illustrate the conceptual framework of the study of silver-based photocatalysis from a wider viewpoint. Moreover, it has the capacity to provide an objective reflection of the progression of development and areas of research interest within a given field, thereby enhancing the efficacy and management of the scientific research.

3. Results and discussion

3.1. Analysis of the Number of Documents Published Over the Years

By assessing the volume of literature published over the given period, annual statistical statistics on the number of papers related to silver-based photocatalysis in the Web of Science (WoS) database can be obtained. As depicted in Fig. 2, the research on study of silver nanoparticles and its derivatives as photocatalysts created an up and down trend with a spike in the number of publications in 2019. Meanwhile, until April 2023 the published papers are 78 documents from 1,941 articles revealed from WoS database. However, based on the trend of publications in previous years, it is predicted that the number of issued literature on this topic will gradually increase by end of the year. This is because the photocatalytic properties of noble metal (silver) have attracted much attention from researchers after showing a great performance under the UV-Vis-NIR spectrum [35,36].

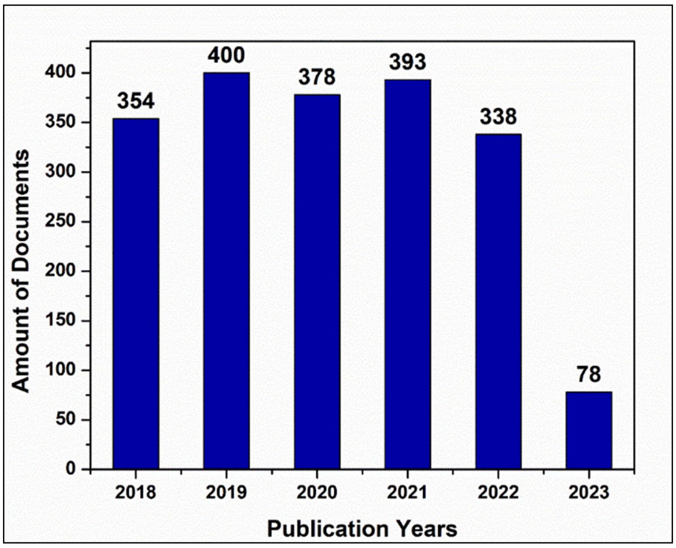

Fig. 2. Yearly variance curves pertaining to articles published on the utilisation of silver nanoparticle and its derivatives as photocatalyst

3.2. Bibliographic Coupling and Co-Occurrence Analysis

The present bibliometric study focuses on two main topics: bibliographic coupling analysis and co-occurrence analysis of the number of entries, such as authors, journal sources and keywords, contained in the literature discussing silver-derived photocatalyst. The implementation of this visualisation analysis helps to understand the data. It also improves the overall comprehensiveness and intuitiveness of the findings.

3.2.1. Analysis Bibliographic Coupling

The concept of bibliographic coupling analysis states that when two or more scientific papers share references, it indicates a meaningful relationship among them [37,38]. Bibliographic coupling helps researchers for better understanding the connections between potential research hotspots and preparing for future studies that aim to more precisely identify the most influential authors, documents, and sources in a given field [39]. In this study, those with six or more publications in indexed journals were set as the visualisation threshold to generate the clustering visualisation results. According to a prior bibliometric study by Guo et al., the required minimum number of publications for an author to be considered a core author in a field is 5.95 [40]. Also, this action is carried out to prevent the visualisation map from being cluttered with nodes, which could result in blurry visualisation results.

3.2.1.1. Author Collaboration

To learn about the most recent advancements in the research on silver-derived photocatalyst and facilitate future research in tracing the history of previous researchers, it is required to conduct an analysis of the key authors, whose contributions to the area have received the maximum number of citations. In this bibliometric study, 1,941 scientific publications were revealed from the contributions of 8707 authors. However, only 301 contributors were visualized and discussed in this paper. They are the authors who successfully published many high impact articles on silver-based photocatalysts and most cited by the other researchers.

Fig. 3a) illustrates the interconnection map of published authors which provides information about the core authors on the mentioned topics and describes the strength of the links between one author to the other.

The size of each node on that map indicates the number of publications associated with that author, and each node on that map represents an author. The larger the circle, the greater the number of documents that have been published by the author. Furthermore, the strength of the collaboration between authors is shown by the thickness of the line connecting various nodes. Fig. 3b) demonstrates how closely related Lei Zhang is to other authors like Pardeep Singh, Peng Wang, Jing Li, Mehrorang Ghaedi, Pengfei Zhu, etc. It was found that Lei Zhang is the most prolific author, as he has been able to publish a total of 13 documents over the course of the past five years and has become the most cited author, having been cited 587 times.

3.2.1.2. Analysis of Publication Source

Through a bibliometric study of the average publication and average citation frequency of a scientific journal, this study can assess journals that are active in the field of silver nanoparticle-based photocatalysts. According to the statistics, the 1,941 documents that were gathered came from 345 different journal sources. TABLE 2 provides information regarding

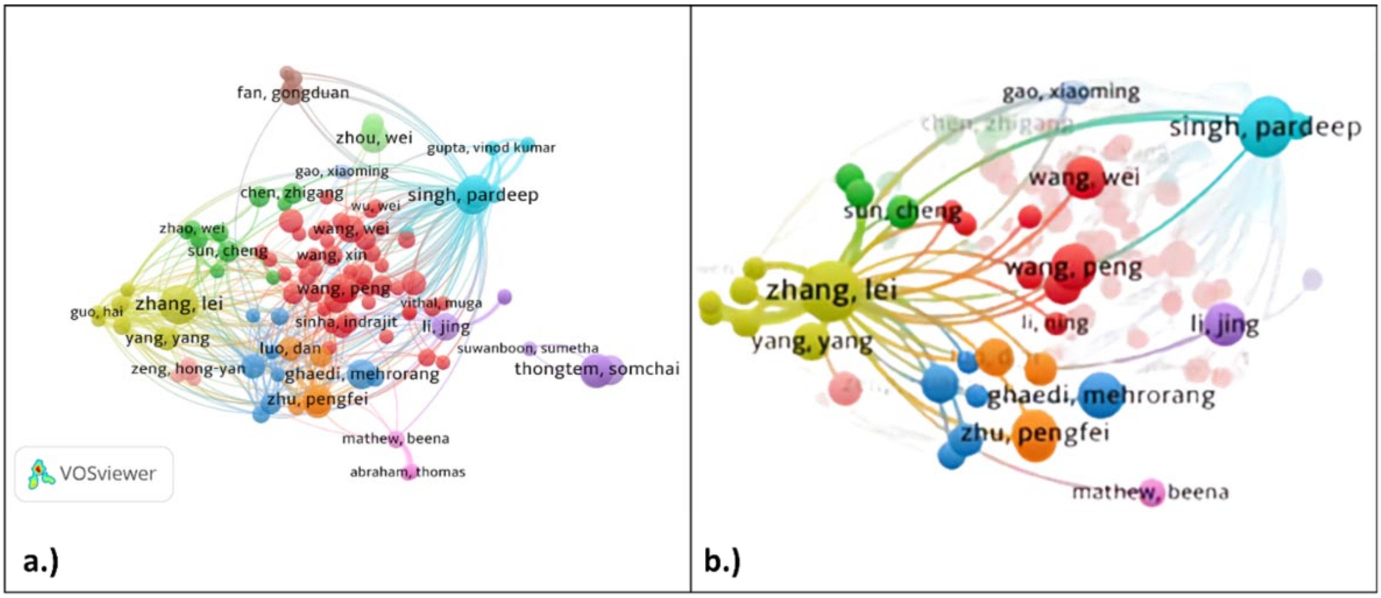

Fig. 3. a) Interconnection of core authors and b) Cooperation of the most cited author

TABLE 2

The top 15 of productive journals on photocatalyst silver nanoparticle and its derivatives

Rankings	Journal Name	Number of Documents	Citation	Impact Factor
1	Applied Surface Science	89	2495	7.392
2	Journal of Alloys and Compounds	64	1246	6.372
3	Chemical Engineering Journal	55	3156	16.744
4	Journal of Materials Science-Materials in Electronics	51	478	2.779
5	Journal of Environmental Chemical Engineering	49	636	7.968
6	RSC Advances	47	407	4.036
7	Journal of Photochemistry and Photobiology A Chemistry	46	920	5.141
8	Colloids and Surfaces a Physicochemical and Engineering Aspects	44	643	5.518
9	Separation and Purification Technology	37	1086	9.136
10	Ceramics International	36	548	5.532
11	Environmental Science and Pollution Research	36	389	5.190
12	Catalysts	33	186	4.501
13	Inorganic Chemistry Communications	33	1089	3.428
14	Journal of Colloid and Interface Science	32	170	9.965
15	Journal of Hazardous Materials	28	1639	14.224

the top 15 journals in terms of the total number of published documents and the citations received by those documents. Also, the table lists the impact factors for each journal. Looking at the number of documents that have been published, it can be noticed that Applied Surface Science occupies the first place as the main source journal for authors to publish their scientific papers. In the last 5 years, there are 89 documents that have been submitted in this journal.

The second place is assigned to Journal of Alloys and Compounds with 64 documents, then Chemical Engineering Journal, Journals of Materials Science-Materials in Electronics, and Journal of Environmental Chemical Engineering are the third, fourth, and fifth places with the number of documents that have been published are 55 documents, 51 documents, and 49 documents, respectively. Then, it was found that the number of citations of each journal is contrary to the ranking order of journals, but in line with the impact factor of the journal. In other words, the higher the citation and submitted paper to the journal, the greater the journal's impact factor. It can be reflected in the Chemical Engineering Journal, which has an impact factor of 16.744 after being cited 3156 times and 55 documents submitted to this journal. Furthermore, the top 15 journals are interdisciplinary, with most of them in environmental categories, which implying there is a growing environmental interest in studying silver nanoparticles and their derivatives as a photocatalyst.

3.3. Analysis The Co-Occurrence of Keywords

Clustering the co-occurrence of the keywords can reveal the core and research topic of an article by identifying the frequency of keyword's appearance across a set of documents. Furthermore, through the analysis of keywords, it is possible to identify research hotspots within a specific field. In this study, a total of 3656 author's keywords have been analysed, but only about 209 keywords meet the threshold, that is, those mentioned by the author with a frequency of at least 6 times and above in the documents, and then the results are displayed on the visual scientific landscape in Fig. 4. The figure is a density visualization, in which each point in the visualization of item density has a colour that represents the density of objects there. Colours are typically arranged in the order of violet, indigo, blue, green, yellow, orange, and red, which are the hues that make up a rainbow. When the colour of the point is closer to red, the more objects are nearby and the heavier the weights of those objects are. In the opposite direction, a point's colour closer to violet showing fewer objects nearby and the lighter the weights of those objects.

Based on Fig. 4 also, most of the documents included in this study have the keywords "photocatalysis" in their work. This is in accordance with the objective of this study, which is to learn about the photocatalytic activity of photocatalysts, particularly for those derived from silver particles. In the map, silver materials in photocatalysis have become a research hotspot, where the existence of silver nanoparticles in photocatalysis shows its existence with its presence in 111 keywords in the literature that was examined. Then followed by Ag_3PO_4, AgBr, AgCl, Ag_2O, Ag_2S, and AgI with each keyword has been mentioned by the authors as much as 108, 43, 27, 20, 17, and 6, respectively. In addition, it is seen that research has also been conducted on the photocatalytic activity of the hybrid photocatalyst made up of composite or heterojunction structure of Ag/AgCl, Ag-TiO_2 and Ag-ZnO.

Moreover, the map also shows that so far, research hotspots have only focused on the use of visible light to irradiate photocatalysts. However, the spot in which discussing the use of sunlight, an inexhaustible energy, is still lacking. This can be used as a foundation or main idea by future researchers in examining the photodegradation of materials under solar irradiation. Then, from these facts, there is a research gap that can be fulfilled by further research such as intensifying research on AgCl, Ag_2O, Ag_2S or AgI in their work because the data shows that those silver derivatives are still very rarely studied for their photocatalytic activity. In addition, it can also be seen that research

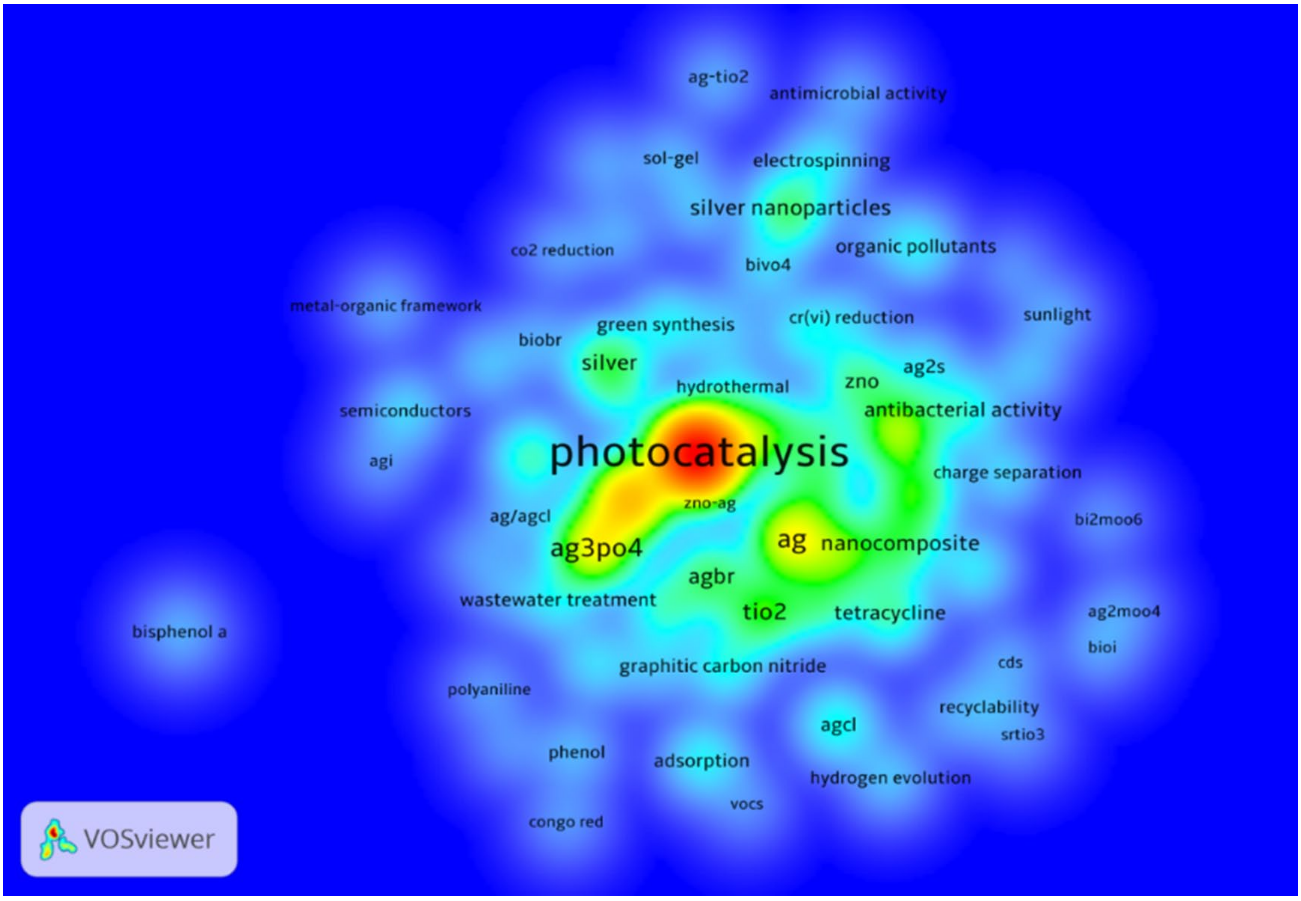

Fig. 4. Density visualization of authors keyword on study of the utilization of silver nanoparticle and its derivatives as photocatalyst

on hybrid photocatalysts consisting of more than two types of materials in a heterojunction structure is still limited. In fact, previous studies also shows that by using three or more layers of heterojunction structure photocatalyst can expand the light spectrum utilized in photocatalysis, i.e. ultraviolet-visible-near infrared spectrum [41].

4. Conclusions

To understand the growth, research gap, and trends in research on silver-based photocatalysts, this review analyses the scope of study on silver nanoparticles within photocatalysis using a bibliometric investigation and scientific landscape visualisation method with the help of VOSviewer application. Reference manager application called Publish or Perish was used to harvest publication data from the Web of Science (WoS) Core Collection. Silver nanoparticle and its derivatives as photocatalysts research has an up-and-down tendency, with a peak in 2019 publications. Currently, quarter year of 2023 has the fewest paper publications, with 78 from 1,941 WoS papers and is expected to increase by the end of the year. Over the past five years, Lei Zhang has published 13 documents and been cited 587 times, making him the most prolific author. Journal of Applied Surface Science becomes the most popular platform for publishing the related research work, where it has published 89 papers in the last five years. The co-occurrence study implies that the publications considering the utilization of sunlight, an unlimited energy, is still missing. This can be utilized by future researchers to study solar-induced photodegradation of materials. Moreover, there is a research gap that can be filled by strengthening study on silver derivatives including AgCl, Ag_2O, Ag_2S, and AgI for photocatalytic activity.

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