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Review Article

Advancements and global perspectives in the green synthesis of silver nanoparticles: A two-decade analysis

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Abstract

Silver nanoparticles, also known as AgNPs, have earned significant attention from scientists due to their remarkable physicochemical characteristics. These traits encompass potent antibacterial effects, plasmonic activity, and a notable surface area-to-volume ratio. The conventional methods for synthesizing (AgNPs) typically involve the use of hazardous chemicals. This practice not only poses risks to the environment and human health but also goes against the core principles of sustainability that underpin modern scientific research. This has led to the concept of "green synthesis," which pertains to the utilization of natural resources, including plant extracts, microbes, and biomolecules, with the intent of filling the role of stabilizing and reducing agents. Bibliometric research analyzes systematic literary data statistically. This study used bibliometric indicators to examine, map, and evaluate global green synthesis research output on AgNPs. A Scopus search was performed to find all English-language peer-reviewed scientific works on AgNPs produced in the last two decades. Bibliometric indicators were determined using VOSviewer and Biblioshiny. We made thematic, conceptual, and visualization charts. A grand total of 4079 published documents were obtained. Indian authors exhibited the highest level of activity, accounting for around 41.8% of the overall publications. Conversely, researchers from the United States (USA) demonstrated the most substantial scientific influence. The findings of the study indicate a lack of substantial international collaboration within the scope of this research domain. The process of keyword mapping has successfully identified the primary areas of research focus and current trends within this particular field of study. The key clusters identified through theme and hotspot analyses included multimodal techniques in biosynthesis and characterization, antibacterial and antifungal action, in addition to anticancer, antioxidant activity, and apoptosis. The present work undertook an analysis and mapping of the growing domain of green synthesis research of (AgNPs), while also identifying diverse applications associated with AgNPs. AgNPs were employed as drug delivery systems in order to selectively target cancer cells and enhance the bioavailability of anticancer drugs. The study demonstrated the potential of customizing these NPs for precise medication administration by including biocompatible chemicals through biofunctionalization. Moreover, AgNPs have been applied in diagnostic imaging due to their good optical characteristics. However, clinical research is still required in order to transform this fundamental insight into formulations that are clinically useful.

Keywords

antibacterial, anticancer, bibliometric study, characterization, drug delivery, nanotechnology

Introduction

Nanoparticles, which are materials characterized by their nanometer-scale dimensions, have garnered substantial consideration from the scientific community owing to their distinctive and adjustable features. These properties have been utilized in numerous disciplines, including electronics, medicine, catalysis, and materials research (Moghimi and Hamad 2009; Zhang et al. 2016; Alshaer et al. 2019; Xu et al. 2020; Gharaibeh et al. 2021; Lafi et al. 2021; Yaghmur and Hamad 2022). Scientists are particularly interested in silver nanoparticles, or AgNPs, due to their extraordinary physicochemical properties, which include a high surface area-to-volume ratio, potent antibacterial properties, and plasmonic activity (Riaz Ahmed et al. 2017; Matalqah et al. 2020; Telfah et al. 2023; Wasilewska et al. 2023).

As the investigation of these minuscule wonders advances, it becomes progressively apparent that traditional approaches to the synthesis of AgNPs frequently entail the utilization of perilous chemicals, energy-demanding procedures, and severe circumstances (Aria 2017; Shnoudeh et al. 2022). The consequences of these processes extend beyond their environmental and health implications, as they also contravene the fundamental ideals of sustainability that serve as the foundation of contemporary scientific study.

The concept of "green synthesis" has emerged as a significant paradigm shift in the field of nanoparticle creation (Samuel et al. 2022). During the synthesis of AgNPs, "green synthesis" relates to the utilization of natural resources, including plant extracts, microorganisms, and biomolecules, as stabilizing and reducing agents. This novel methodology adopts the tenets of green chemistry, with the objective of reducing the ecological consequences of synthesis protocols and promoting sustainable methodologies (Gour and Jain 2019). Other green chemistry approaches for AgNP synthesis include polymer or surfactant template synthesis, such as the in situ reduction of AgNO3 by polyethylene oxide, UV-induced reductive protocols in the presence of biopolymers like chitosan, and electrochemical top-to-bottom approaches for creating bulk-to-nano silver. The utilization of green synthesis methods for the production of AgNPs offers a compelling option due to its ability to substantially decrease or eliminate the requirement for hazardous chemicals, reduce energy consumption, and minimize the ecological impact.

The fusion of AgNP synthesis with green principles carries profound significance, both in terms of scientific innovation and ecological responsibility (Alwhibi et al. 2021; Liaqat et al. 2022). The investigation of green synthesis approaches presents a prospect not only to utilize the distinctive characteristics of AgNPs but also to accomplish this in a manner that is consistent with wider global sustainability objectives (Liaqat et al. 2022). This approach demonstrates a deliberate endeavor to reconcile scientific progress with environmental awareness, highlighting the compatibility of knowledge acquisition and the conservation of our natural environment.

In light of the increasing attention and promise surrounding the environmentally friendly production of AgNPs, it is of essential importance to carry out a thorough evaluation of the present state of research in this field. Additionally, a consideration of relevant patent literature highlights the practical advancements and industrial applications in the synthesis of AgNPs, complementing the insights from scientific publications (Ortashi 2017). A comprehensive knowledge of the intricate relationship among new synthesis processes, the properties shown by the resultant nanoparticles, and their many applications is needed, surpassing the limitations of traditional methodologies. This work utilizes analysis as a methodological approach to comprehensively examine the research landscape. By conducting an examination of publication trends, notable contributors, collaboration networks, and citation patterns, a more intricate depiction arises, providing a clearer understanding of significant observations that might inform future research directions (Aleidi et al. 2024; Bustanji et al. 2024; Bustanji et al. 2023a; Bustanji et al. 2023b).

This paper aims to analyze the current state of the green synthesis of AgNPs. The following sections will examine the emergence of green synthesis as a response to the limitations of conventional methodologies, the diverse significance of AgNPs for various applications, and the ecological considerations that underpin the incorporation of green principles. In addition, the present study provides a summary of the rationale and scope of the bibliometric analysis, elucidating the methodological framework that serves as the investigation's foundation. In this paper, we will explore the bibliometric results, analyzing notable contributions, emerging patterns, and prospective future directions for research on green synthesis in the AgNP field.

Methods

Search strategy and honing the retrieved papers

A search into the Scopus database was conducted on August 8, 2023, with the purpose of identifying as well as assessing the global research outputs pertaining to the study the green synthesis of AgNPs over the last two decades. The search term ("silver nano*" OR "silver-nano*" OR "Ag nano*" OR "ag-nano*") AND ("Green Synthesis") included keywords, titles, and abstracts.

Solely studies that were published in English journals that were subjected to peer review during the years 2002 and 2022 were taken into consideration. The search excluded materials like reviews, press releases, letters, notes, errata, conference articles, editorials, and other forms of publications. Conference proceedings, book chapters, as well as publishing in books were also omitted.

Data export

In order to facilitate further investigation, the documents acquired were converted to CSV file format. The examination of bibliometric data necessitated the utilization of Microsoft Office Excel 365 (Microsoft Corporation, Redmond, WA, USA) and the Scopus platform. This enabled the gathering of information across diverse fields of study and publishing journals. The documents were kept in CSV file type in order to facilitate additional analysis.

Bibliometric analyses and visualization

This study utilized the latest iteration of the Visualization of Similarities software, VOSviewer 1.6.18, to evaluate as well as map collaborations, citations, and keywords within the gathered documents. The VOSviewer mapping technique, along with cluster analysis, was employed in order to reveal international network partnerships, author-author networking, and author keywords. In addition, the cluster density maps were applied for illustrating all keywords. The Biblioshiny program, which is a constituent of the Bibliometrix package, was chosen to conduct supplementary analyses on author keywords (Aria 2017; Moral-Munoz et al. 2020). Employing this software permitted the identification of patterns and the investigation of areas of focus through the analysis of trends in author keywords (Moral-Munoz et al. 2020).

We performed a manual verification of the names and initials of prominent researchers when evaluating authors' bibliometric indicators in order to ascertain correctness. We subsequently consolidated authors having distinct initials, who were formerly classified as two separate independent entities, by utilizing a thesaurus file to establish a unified designation. Similar methodologies were utilized to be involved in analyses of the participating countries and keywords. As a part of the keyword analysis process, related or synonymous keywords were amalgamated in a singular term. The utilization of Biblioshiny and VOSviewer, two software tools, facilitated the possibility for undertaking such alterations (van Eck and Waltman 2010; Aria 2017).

Results

Yearly analysis of the publications

Using the search terms "silver nano*" AND (green synthesis), a comprehensive search was carried out to retrieve publications pertaining to the study on the green synthesis of AgNPs between 2003 and 2022. The search obtained an overall total of 4079 documents that were relevant. Among the previously mentioned documents, a plurality of 1827 (equivalent to 44.8%) were released during the most recently three-year period, which covered the years 2020 to 2022. Fig. 1 demonstrates the curve of the annual volume of research documents that are constructed.

The analysis of participating journals

In total, 4079 documents were gathered from a selection of approximately 921 peer-reviewed journals that are indexed in Scopus. Nonetheless, merely 42 journals disseminated at least 20 documents. Rankings of the 10 most widely read, along with frequently published journals, are displayed in Table 1. Amongst the journals, the Journal of Cluster Science emerges as the most prolific, having published 72 publications, which accounts for 1.8% of the total number of publications. Following closely behind is Nanomaterials, which has published 64 articles. Nine out

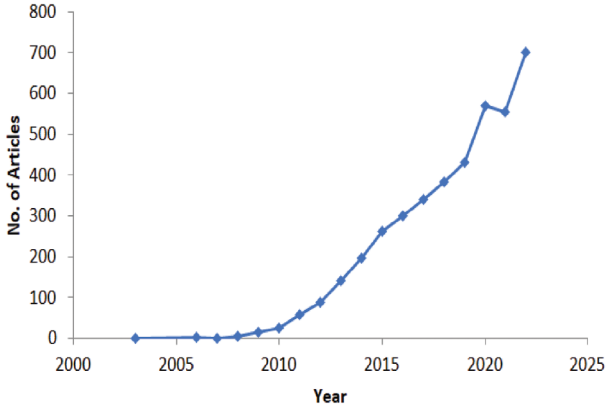

Figure 1. The growth of annual scientific production (From 2002 to 2022).

Table 1. The ten leading active journals publishing documents.

The Journal Name	No of publication	%	Citations	Scopus Percentile (Q)
Journal of cluster science	72	1.8	1442	77 (Q1)
Nanomaterials	64	1.6	1766	81 (Q1)
International journal of nanomedicine	59	1.4	5149	96 (Q1)
Materials science and engineering C	56	1.4	4304	89 (Q1)
RSC advances	56	1.4	2266	78 (Q1)
materials letters	53	1.3	3414	79 (Q1)
journal of photochemistry and photobiology b: biology	52	1.3	3204	99 (Q1)
Molecules	52	1.3	1662	78 (Q1)
Applied nanoscience (switzerland)	51	1.3	3460	76 (Q1)
Bionanoscience	50	1.2	810	64 (Q2)

of the ten journals that have the highest ranking are classified as Q1 in accordance with Scopus.

The analysis of articles

The articles that were acquired for analysis demonstrate an h-index of 160 along with a cumulative citation count of 145,697. Each individual document within the dataset earned 75.7 citations on average. Furthermore, it has been noticed that a total of 831 documents have been encountered with citations that are equal to or greater than ten. Table 2 exhibits the 10 documents with the highest citation counts, along with their annual citation normalization.

The analysis of authors

A total of 14,025 authors participated in the publications that were collected, with an average number of 3.4 authors for each document. Concerning the aforementioned authors, a total of 25 researchers have made significant contributions by publishing at least 15 or more publications. A list of the 25 authors with the highest level of activity is provided in Table 3. Rajeshkumar S., who is associated with the Department of Pharmacology at Saveetha University in India, emerged as the most productive author, having contributed 50 published documents, which accounts for 1.2% of the overall publications.

The active countries

The examination of our study keywords yielded findings displaying that 109 different countries overall have contributed to the publishing of this particular area in Scopus. Table 4 illustrates the countries with the highest rank in terms of publication quantity, featuring the ten leading countries. There were 66 countries that published

Table 2. The ten most frequently cited documents concerning AgNPs-GS research.

Rank	Authors	Title	Year	Number of citations	Normalized Citations/year	Journal
1st	Raveendran P. et al.	Completely "Green" Synthesis and Stabilization of Metal Nanoparticles	2003	2004	95.4	J Am Chem Soc
2nd	Bar H. et al.	Green synthesis of silver nanoparticles using latex of Jatropha curcas	2009	838	59.9	Colloids Surf A Physicochem Eng Asp-A
3rd	LI S. et al.	Green synthesis of silver nanoparticles using Capsicum annuum L. extract	2007	829	48.8	Green Chem
4th	Sathishkumar M. et al.	Cinnamon zeylanicum bark extract and powder mediated the green synthesis of nano-crystalline silver particles and thier bactericidal activity	2009	813	54.2	Colloids Surf B Biointerfaces
5th	Anandalakshmi K. et al.	Characterization of silver nanoparticles by the green synthesis method using Pedalium murex leaf extract and their antibacterial	2016	609	76.1	Appl Nanosci (Switzerland)
6th	Vigneshwaran N. et al.	A novel one-pot 'green' synthesis of stable silver nanoparticles using soluble starch	2006	603	33.5	Carbohydr Res
7th	Philip D. et al.	Green synthesis of gold and silver nanoparticles using Hibiscus rosa sinensis	2010	576	41.1	Physica E.
8th	Khalil M. et al.	Green synthesis of silver nanoparticles using olive leaf extract and its antibacterial activity	2014	555	55.5	Arab J Chem
9th	Ahmad N. et al.	Rapid synthesis of silver nanoparticles using dried medicinal plant of basil	2010	534	38.1	Colloids Surf B Biointerfaces
10th	Jain D. et al.	Synthesis of plant-mediated silver nanoparticles using papaya fruit extract and evaluation of their anti-microbial activities	2009	492	32.8	Digest Journal of Nanomaterials and Biostructures

Table 3. The top ten authors publishing documents on green synthesis of AgNPs.

Rank	Author	Documents (%)	Citation
1st	Rajeshkumar S.	50 (1.2)	675
2nd	Benelli G.	38 (0.9)	2355
3rd	Govindarajan M.	32 (0.8)	1149
4th	Wang Y.	28 (0.68)	1079
5th	Kumar S.	27 (0.66)	1132
6th	Wang X.	27 (0.66)	755
7th	Kumar V.	26 (0.64)	848
8th	Murugan K.	24 (0.56)	2014
9th	Kumar A.	22 (0.54)	475
10th	Nicoletti M.	21 (0.52)	1428
10th	Singh P.	21 (0.52)	1683

Table 4. The top ten active countries in publishing documents on the green synthesis of AgNP.

Rank	Country	Number of publications (absolute research output)	% of Total documents	Total Citations	Citation / Document
1st	India	1707	41.8	67887	39.8
2nd	China	401	9.8	15224	38.0
3rd	Iran	391	9.6	15749	40.3
4th	Saudi Arabia	372	9.1	11501	30.9
5th	South Korea	257	6.3	12779	49.7
6th	Egypt	248	6	8177	33.0
7th	Pakistan	231	5.7	5731	24.8
8th	United States	153	3.8	9201	60.1
9th	Malaysia	143	3.5	6387	44.7
10th	Turkey	132	3.2	2735	20.7

5 papers and above and 18 countries with 50 publications and above.

The subject has recorded that Indian scholars have made substantial contributions, authoring 1707 papers, which represent 41.8% of the total publications. Chinese researchers have made notable contributions, producing 401 documents, which account for 9.8% of the overall publications. With 391 articles published, or 9.6% of total publications, Iranian scholars rate in the third place. American articles recognize with the highest scientific impact, averaging 60.1 citations for each document, therefore exceeding the publications from South Korea regarding this respect.

The bibliometric mapping

International collaboration

The VOSviewer software gives significant knowledge about national trends in publication and collaboration. This software facilitated an investigation of international collaborations and partnerships, culminating in the development of a network visualization map (Fig. 2). The map depicts countries as spheres, as shown in Fig. 2A, with the size of each sphere reflecting the number of published publications. Nonetheless, as illustrated in Fig. 2B, nations with larger spheres demonstrate a higher count of citations in the published works. Of 109 countries evaluated, only 18 fulfilled the fundamental criterion of submitting a minimum of 50 publications from their respective countries. The nations were categorized into three definite groups, illustrating the significant coordination among the countries within each category. Seven countries comprise Group 1 (shown in red), including Egypt, India, Nigeria, Saudi Arabia, South Africa, South Korea, and Thailand. Group 2 consisted of seven additional countries, namely Brazil, China, Italy, Mexico, Pakistan, the United States, and the United Kingdom (highlighted in green). Four countries, namely Iran, Iraq, Malaysia, and Turkey, are included in Group 3 (blue color). It has been noted that collaborative publications by authors from the same group of countries are prevalent, likely reflecting a shared scientific interest. In general, visualizing transnational collaborations elucidates trends in publication and patterns of global cooperation.

Analysis of author keywords and hotspots forecasting

The keyword association analysis was performed utilizing bibliometric tools, specifically Biblioshiny and VOSviewer, in order to identify active research domains in the green synthesis of NPs. The analysis concentrated on author keywords, employing a thesaurus file to eliminate synonyms and establishing a minimum occurrence criterion of ten instances.

Table 5 and Fig. 3 show the most prevalent author keywords, each with at least 40 occurrences. A network visualization map of author-keywords is shown in Fig. 3A, with circular nodes highlighting the most prevalent keywords (with 40 or more occurrences). Nodes with the identical color are interconnected, and their size reflects the frequency of connections.

The author keywords that were detected were classified into four distinct clusters. Cluster 1, signified in red, comprises 6 terms: biosynthesis, catalytic activity, characterization, methylene blue, nanoparticles, and surface plasmon resonance.

Cluster 2, denoted in green, encompasses keywords associated with antifungal activity, antibacterial activity, chitosan, green synthesis, plant extract, and AgNPs.

Cluster 3, represented in blue, includes words such as FTIR, TEM, SEM, and XRD.

Lastly, three words pertaining to apoptosis, antioxidant activity, and anticancer activity are included in Cluster 4 (highlighted in yellow). These clusters elucidate the primary research topics and areas related to the green synthesis of AgNPs, enhancing comprehension of the prevailing themes in the field. It is essential to highlight that the results obtained from both Biblioshiny and VOSviewer, two bibliometric software applications, exhibited a clear

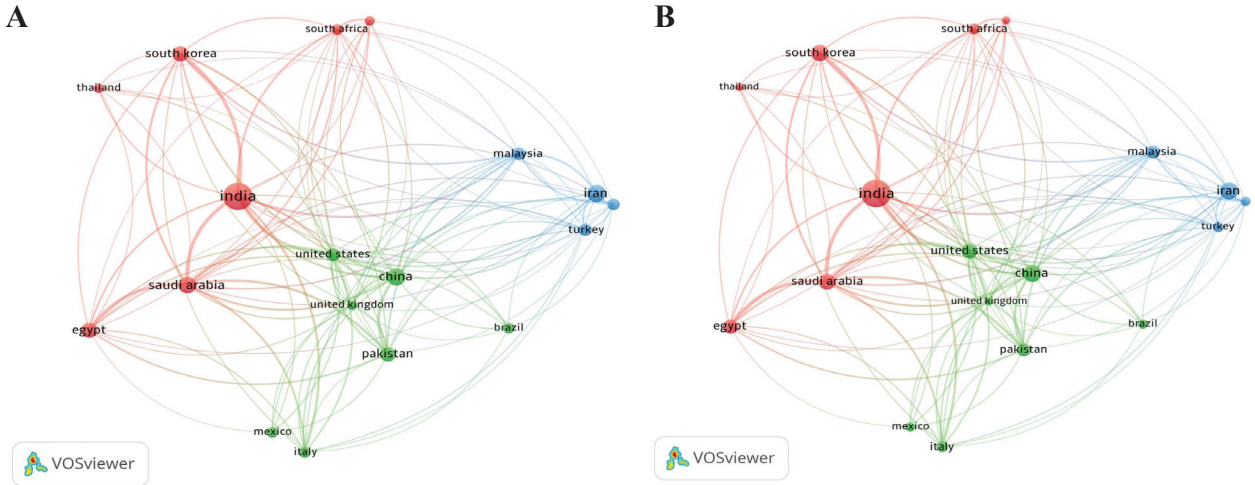

Figure 2. Map of international collaboration on the green synthesis of AgNPs-GS research as a network visualization: **A.** based on the number of the documents; **B.** based on the citations.

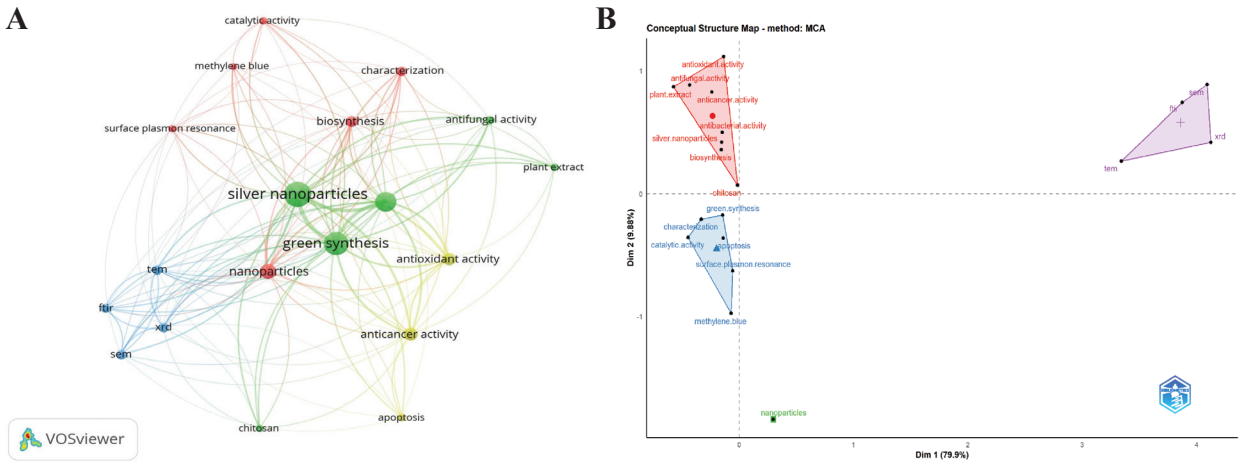

Figure 3. Analysis of the author keywords that appear most frequently. Keywords with a minimum occurrence of 40 times were involved: **A.** Network visualization map acquired by VOSviewer; **B.** Conceptual structure map acquired through Biblioshiny.

Table 5. The highly frequent keywords (40 times and more).

Keyword	Frequency	Clusters
Biosynthesis	154	1
Catalytic Activity	49	1
Characterization	112	1
Methylene Blue	43	1
Nanoparticles	449	1
Surface Plasmon Resonance	49	1
Antibacterial Activity	1149	2
Antifungal Activity	77	2
Chitosan	52	2
Green Synthesis	1910	2
Plant Extract	46	2
Silver Nanoparticles	2406	2
FTIR	97	3
SEM	100	3
TEM	118	3
XRD	109	3
Anticancer Activity	268	4
Antioxidant Activity	247	4
Apoptosis	54	4

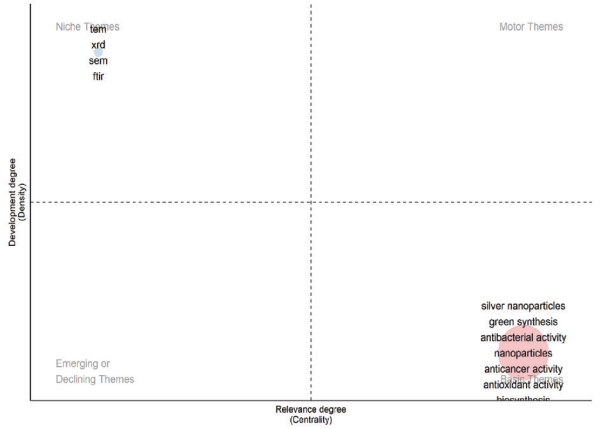

Figure 4. The thematic map obtained from author keyword analyses utilizing Biblioshiny.

resemblance. The resemblance that has been discovered indicates that these clusters represent the main research areas in the field of green synthesis of AgNPs.

Additionally, biblioshiny was employed as the bibliometric tool, and a conceptual structural map was utilized in order to evaluate the clustering of author-keywords (Fig. 3B). Interestingly, these clusters correspond in a close manner with the previously found clusters, suggesting that the interrelations among keywords substantially impact research priorities within the field.

A thematic map was produced using Biblioshiny (Fig. 4) for deeper analysis of the retrieved keywords. In bibliometric investigations, thematic maps are frequently utilized to investigate and display the variety of topics found in an assortment of the published works. The identified keywords were categorized into four overarching thematic groups: motor, niche, emerging, and basic themes. FTIR, SEM, TEM, and XRD have evolved as significant areas of study within the niche themes. These subjects presumably constituted focused and specialized research within the overarching framework of green synthesis of NPs. Diverse research themes and topics pertaining to AgNPs-GS are illuminated by the thematic analysis carried out in this study.

Two complementary methods were performed to attain a more profound understanding of the keyword analysis of the authors. The first method was constructing a normalized overlay of keyword clusters based on the average publication year, as shown in Fig. 5A. The color-coded clusters in the figure denote author keywords categorized by their publication dates, with yellow signifying keywords published lately. This visualization offers a comprehensive overview of the evolution of several keyword clusters. The second method employed Biblioshiny to visualize trending topics, as presented in Fig. 5B. This analysis indicated that anticancer activity, antioxidant activity, and antifungal activity were the predominant author keyword trends in the field of research. By examining trending topics, researchers can discern the shifting interests and priorities in the green synthesis of AgNPs. Both methodolo-

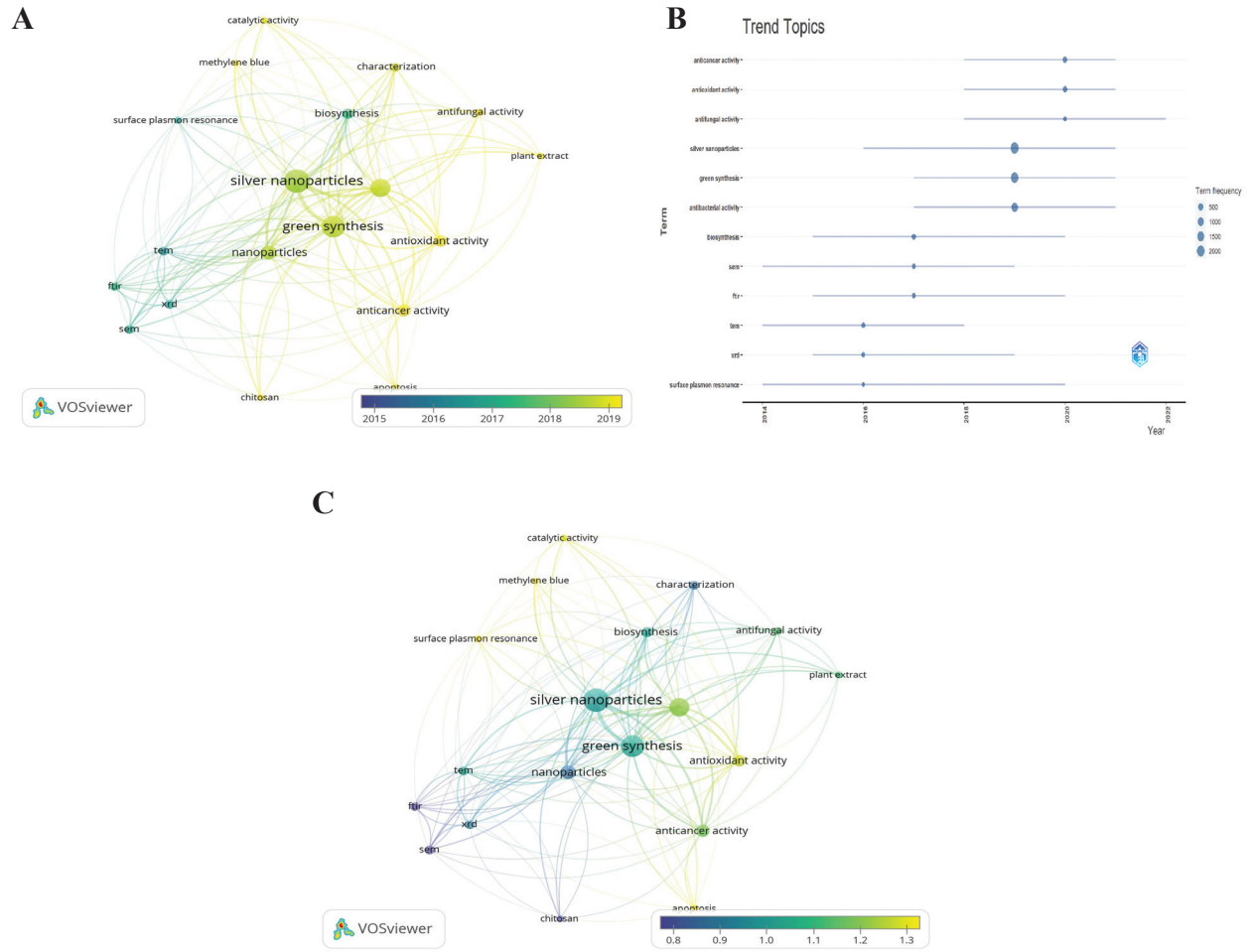

Figure 5. A. Overlay visualization map depicting the highest occurrence of author keywords alongside the average publication year overlay; **B.** Author keyword trends; **C.** Overlay visualization map depicting the highest occurrence of author keywords, accompanied by an overlay of average normalized citations.

gies produced consistent findings, hence emphasizing the robustness of the results. The count of citations exhibited significant variability among distinct author keywords. To mitigate the impact of publication age on citation counts, the publication date was employed to normalize citations, facilitating an equitable comparison among various timeframes. For the author keywords under examination, Fig. 5C shows the normalized mean number of citations. The author keywords "anticancer activity," "antioxidant activity," and "antifungal activity" exhibited the highest normalized citation counts, signifying their substantial influence and prominence in the research literature. In the field of green synthesis of AgNPs, these data offer a thorough insight into the topical foci, temporal trends, and citation impacts of author keywords. These findings add to the growing knowledge base and assist researchers in pinpointing key areas of interest and prospective directions for subsequent study.

Analysis of all keywords

The study additionally investigated the correlations among all keyword terms that were present in scholarly article titles and abstracts. A cluster density map, as illustrated in Fig. 6, visualizes the co-occurrences of these keywords, with a minimum threshold of 100 occurrences per term for inclusion. Out of 17,523 evaluated words, only 121 words met the criterion of having 100 or more occurrences. These words were later represented in the cluster density map (Fig. 6). The frequency of occurrences is correlated with the relative intensity of the colors on the map, while words of the same color imply a notable correlation.

Discussion

Green synthesis of AgNPs has attracted remarkable focus as a promising avenue for investigating various biomedical applications, with a particular focus on cancer research. These AgNPs exhibit remarkable attributes, such as their capacity to be tailored for targeted drug delivery through biofunctionalization with biocompatible molecules (AlKhatib et al. 2006; Aiedeh et al. 2007; Wang et al. 2012; Ahn and Kim 2022), in addition to their advantageous optical characteristics, enabling their utility in di-

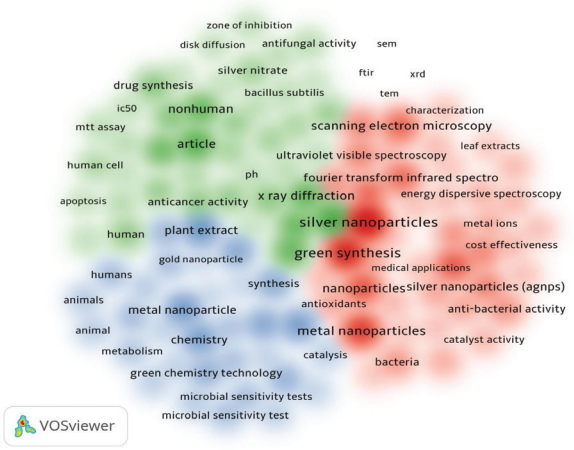

Figure 6. Cluster density among all keywords.

agnostic imaging (Ahn and Kim 2022). While the initial findings regarding the potential advantages of AgNPs in cancer therapy are promising, further extensive investigations are essential to comprehensively unravel their potential uses and to validate their safety and efficacy in clinical settings for the benefit of patients (Bin-Jumah et al. 2020).

The analysis of bibliometrics is crucial in scientific research, facilitating a comprehensive evaluation and visual depiction of vast knowledge repositories. This current study endeavor is to address existing gaps in our understanding by providing a quantitative summary of global investigations into AgNPs, specifically within the realm of green synthesis research. To accomplish this goal, we compiled relevant scientific literature from the esteemed Scopus database, recognized for its reputation as the most extensive repository of peer-reviewed publications, comprising citations and abstracts. Scopus, through its numerous search functionalities along with comprehensive analytical tools, permits data extraction to conduct further visualization and exploration. Journals indexed in Scopus conduct meticulous peer-review processes and stringent evaluations, fostering their trustworthiness. Along with that, Scopus categorizes these journals according to their topic matter, rendering it a comprehensive source for individuals exploring the sphere of green synthesis of AgNPs research. Insights gained from our study convey significant perspectives that mentor institutions and researchers in prioritizing their endeavors and pointing future inquiries in this emerging sector.

This study carried out an in-depth search to gather all pertinent literature addressing the green synthesis of AgNPs across the past two decades. This study solely featured reviews and papers that encountered a comprehensive peer-review process and were composed in the English language. The outcomes revealed a considerable increment in articles in this specific domain over the preceding three years, with approximately 44.8% of the papers published from 2018 to 2022 (Fig. 1). A total of 4079 papers were extracted from 921 publications indexed in Scopus. As Table 2 illustrates, the most fruitful top 10 journals published around 14% of all articles distributed. The acquired documents yielded a total of 145,697 citations, averaging 75.7 citations per document. Furthermore, the published publications manifested a 160 h-index, implying a significant level of reader engagement. The Journal of Cluster Science has demonstrated the highest citation count. The frequently referenced documents were published between 2003 and 2016, as shown in Table 2. Nonetheless, the recent publications were unable to achieve adequate citations to compete with these previously mentioned documents. The scholarly publication by Raveendran P. et al., published in the Journal of American Chemical Society (Raveendran et al. 2003), received the highest count of citations across all the retrieved documents. The essay investigates a sustainable method for synthesizing AgNPs, employing a straightforward, highly effective, and ecologically friendly process. In addition, the aforementioned paper collected the highest number of citations annually.

In light of a geographic distribution analysis of the obtained papers, academics from India contributed the greatest number of publications, with 1707 documents (41.8%). Subsequently, researchers from China authored 401 documents (9.8%). The analysis of the scientific influence of these countries, as evidenced by the average citations per document, reveals that documents from the United States possess the greatest total scientific impact (60.1 citations/doc). Following that, South Korea ranks second with 49.7 citations per document, whereas Malaysia occupies the third rank with 44.7 citations per document (Table 4, Fig. 2). The documents that were gained accumulated a total of 145,697 citations for the focus of this research. The noteworthy nature of this topic is made evident by its significant citation count, which is reinforced by publications in reputable academic journals. The data provided in Table 1 corroborates this result, revealing that among the top 10 journals, nine of them are listed as Q1, whilst the tenth journal is categorized as Q2. In addition, the study assessed international collaborations among nations in this area of research. The network visualization of international research partnerships, as illustrated in Fig. 2, indicates that the most significant research partnership was designated between India and both Saudi Arabia and South Korea.

Research trends and hotspots

Biblioshiny and VOSviewer were implemented to map hotspots by examining the co-occurrences of author keywords in the collected literature (exceeding 40 instances). As a consequence, four intersecting conceptual clusters consisting of 20 main author keywords were observed. The areas of interest and research focus of the recovered documents are highlighted in these clusters.

The four aforementioned clusters, which were determined by VOSviewer and Biblioshiny, were used to deduce the subsequent hotspots (Figs 4, 5). Cluster 1: Exploring sustainable AgNPs synthesis and its multifaceted applications: (biosynthesis, catalytic activity, characteriza-

tion, methylene blue, nanoparticles, and surface plasmon resonance).

Biosynthesis involves the reduction of silver ions (Ag+) to AgNPs by bioactive compounds found in the chosen biological material. These chemicals function as reducing agents and provide stabilization to the nanoparticles. Biosynthesis provides a wide range of possibilities, enabling the manipulation of various features of AgNPs, such as their size, shape, and surface qualities (Othman et al. 2019). Biosynthesized AgNPs demonstrate a diverse array of potential applications, encompassing antibacterial, antioxidant, and possible anticancer characteristics (Mohanta et al. 2017a). The nanoparticles have generated significant interest in various academic fields, ranging from health to materials science (Gloria et al. 2017; Hamad et al. 2024). Ongoing investigations into the methodologies and uses of biosynthesis are consistently broadening their scope and enhancing their practicality.

Among green synthesis approaches, the utilization of natural sources like plant extracts, microorganisms, and biomolecules has gained significant attention (Mukunthan et al. 2011). An essential aspect of green synthesis involves the catalytic activity of AgNPs, a property that holds immense promise for various fields (Mahiuddin et al. 2020). Green synthesis approaches leverage the inherent reducing and capping capabilities of biological entities, enabling the synthesis of AgNPs without the need for hazardous chemicals. The nanoparticles possess a significant characteristic known as catalytic activity, which plays a pivotal role in enabling various catalytic applications. The catalytic potential of AgNPs encompasses diverse reactions, including reduction, oxidation, and degradation processes (Bolla et al. 2020). Their unique surface properties and high surface area make them efficient catalysts for various chemical transformations. These properties render them particularly attractive for catalytic applications in fields such as environmental remediation, energy conversion, and industrial processes. Within the realm of catalysis, AgNPs assume a crucial function in augmenting the rates of reactions and improving their selectivity. The inherent adjustability of AgNPs enables precise control over their catalytic performance, rendering them highly advantageous in the field of catalysis investigation.

The way AgNPs interact with methylene blue, a common dye with a variety of uses, is one fascinating aspect of AgNPs (Parasuraman et al. 2020). Interactions between AgNPs and methylene blue could find use in sensing and wastewater treatment, among other areas (Palani et al. 2023). AgNPs have the ability to absorb methylene blue, changing their optical and chemical characteristics. The potential of this interaction in colorimetric and spectroscopic investigations has drawn attention, indicating that it presents a possible avenue for sensitive detection approaches. AgNPs and methylene blue work well together in catalytic processes as well. In these instances, AgNPs have been demonstrated to accelerate methylene blue's breakdown, which advances the field of environmental cleanup (Somasundaram et al. 2021).

Another particularly intriguing aspect of AgNPs lies in their interaction with surface plasmon resonance (SPR), an optical phenomenon that enriches their versatility. When AgNPs interact with SPR, a captivating optical phenomenon unfolds. SPR involves the collective oscillation of electrons at the surface of metal nanoparticles, AgNPs included, when illuminated by incident light (Vasil'kov et al. 2018). This phenomenon leads to a resonant amplification in the absorption and scattering of light, resulting in distinctive spectral characteristics. The interplay between AgNPs and SPR has become a focal point of exploration, particularly in the context of sensing and detection (Li et al. 2023).

AgNPs' ability to modulate SPR offers promising avenues for ultrasensitive sensing technologies. By functionalizing AgNPs and monitoring changes in their SPR response upon interaction with specific analytes, researchers have developed cutting-edge sensing platforms with applications ranging from healthcare to environmental monitoring (Li et al. 2023).

Furthermore, the SPR properties of AgNPs extend their influence to enhance the performance of various optical devices, including photodetectors and imaging systems. These unique optical characteristics enable precise control of light at the nanoscale, ushering in innovative developments in optics and photonics (Paladini et al. 2023).

Cluster 2: Green synthesis and the enhancement of antimicrobial potential (antibacterial activity, antifungal activity, chitosan, green synthesis, plant extract, and AgNPs): The green-synthesized AgNPs that harness the natural potency of plant extracts, microorganisms, and biomolecules have opened up intriguing avenues, particularly in the context of antibacterial activity. When AgNPs encounter bacterial pathogens, a remarkable interplay unfolds. The innate properties of AgNPs lend them a formidable antibacterial potency (Dakal et al. 2016). Their small size and high surface area facilitate close contact with bacterial cells, enabling efficient delivery of silver ions (Ag+) that disrupt vital cellular processes. This interaction between AgNPs and bacteria has piqued the curiosity of researchers and scientists alike, as it presents a novel and sustainable approach to combating bacterial infections (Tripathi and Goshisht 2022).

The antibacterial potential of green-synthesized AgNPs extends across a spectrum of applications, from healthcare to environmental remediation. Researchers have explored their use in wound dressings, medical equipment, and water purification systems, harnessing their antibacterial prowess to improve public health and safety (Wilkinson et al. 2011).

The antifungal activity of AgNPs is also an attractive area of study. Similarly, the small size and expansive surface area facilitate close contact with fungal cells. This enables the efficient delivery of silver ions (Ag+) and impedes fungal growth. The exploration of this interaction holds promise not only for medical applications but also for agriculture and food preservation (Mehmood 2018; Kale et al. 2021). The antifungal potential of green-syn-

thesized AgNPs finds relevance across multiple domains. Researchers are investigating their use in antifungal treatments (Kale et al. 2021; Matras et al. 2022). By leveraging the antifungal properties of AgNPs, we can potentially mitigate the harmful effects of fungal infections and enhance the sustainability of various industries.

The interplay between AgNPs and chitosan is an enticing subject of investigation. Chitosan, a biocompatible and biodegradable biopolymer derived from chitin, serves as an excellent companion to AgNPs (Penchev et al. 2009, 2010; Mirda et al. 2021). When AgNPs and chitosan converge, they create a symbiotic relationship that enhances the properties and applications of both materials. Chitosan, with its unique molecular structure, provides stability and acts as a capping agent for AgNPs, preventing their aggregation and ensuring their controlled synthesis. The resulting AgNPs-chitosan nanocomposites exhibit exceptional attributes, making them valuable in a myriad of applications across various domains. These nanocomposites find utility in drug delivery systems, wound dressings, and even as catalysts for chemical reactions (Twal et al. 2024). The combination of AgNPs and chitosan holds the potential to revolutionize fields such as medicine (Mondal et al. 2023; Penchev et al. 2010) and materials engineering (Liu et al. 2022; Rezazadeh et al. 2020).

Cluster 3: Characterization techniques in green synthesis of AgNPs (FTIR, SEM, TEM, and XRD Insights): The characterization of green-synthesized AgNPs is highly important. Highly developed and recent techniques such as Fourier-transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), transmission electron microscopy (TEM), and X-ray diffraction (XRD) have been thoroughly used. FTIR, a powerful analytical technique, provides insights into the chemical composition and functional groups present on the surface of AgNPs. It allows researchers to elucidate the molecules involved in the synthesis and stabilization of AgNPs, offering a deeper understanding of their formation (Jyoti et al. 2016). SEM, on the other hand, offers a visual journey into the micro-size of AgNPs. This technique provides high-resolution images, enabling the assessment of particle size, morphology, and distribution. SEM has played a crucial role in unraveling the intricate structures and surface features of green-synthesized AgNPs (Badar and Ullah Khan 2020). Due to its outstanding resolution at the nanoscale, (TEM) has emerged as a primary analytical technique in the process of characterizing AgNPs. TEM enables researchers to investigate individual AgNPs, which makes it possible to examine their size, shape, and crystalline structure with atomic-level precision. Researchers are able to obtain access to vital insights into the morphology and internal atomic arrangements of AgNPs by making use of TEM, which leads to a thorough knowledge of the nanostructural characteristics of AgNPs (Santra et al. 2014).

XRD is the key to unveiling the crystalline nature of AgNPs. This technique enables the determination of the crystal structure and phase purity of AgNPs, offering critical insights into their physical properties (Santra et al. 2014; Koohpeima et al. 2017).

Cluster 4: Bioactive potential of AgNPs (anticancer activity, antioxidant activity, and apoptosis):

The interface of green-synthesized AgNPs with the domain of anticancer research underscores their substantial therapeutic potential. Comprehensive investigations have illuminated the capability of green-synthesized AgNPs, when meticulously engineered and deployed, to demonstrate robust anticancer activity. At the crux of green-synthesized AgNPs' anticancer action lies their diminutive size and impressive surface area, which collectively endow them with the capacity to infiltrate the protective barriers of cancer cell membranes (Wypij et al. 2021). This nanoscale ingress facilitates the controlled release of cytotoxic silver ions (Ag+), a pivotal facet of their anticancer efficacy (Akter et al. 2018; Dakilah et al. 2024). Upon internalization by cancer cells, Ag+ ions engage in a series of intricate molecular interactions, culminating in the disruption of key cellular pathways crucial for cancer cell proliferation and survival.

The research provides a wealth of evidence for the green-synthesized AgNPs' potential as anticancer agents. It has been demonstrated that these NPs obstruct the typical path of cancer cell division, which ultimately leads to cell death. Moreover, it has been proposed that green-synthesized AgNPs induce apoptosis, or programmed cell death, in cancer cells. Two distinct molecular indicators of this process are the activation of the caspase enzyme and DNA fragmentation (Bin-Jumah et al. 2020).

Moreover, green-synthesized AgNPs exhibit notable antioxidant properties that align with their minuscule size and huge surface area. These attributes empower them to engage in complex interactions with free radicals and reactive oxygen species (ROS), which are key culprits in oxidative stress and cellular damage (Keshari et al. 2020).

Studies have elucidated green-synthesized AgNPs' ability to serve as free radical scavengers, effectively neutralizing the harmful effects of ROS. Their high surface reactivity allows for the efficient capture and subsequent elimination of these detrimental species. This antioxidative potential has sparked interest in AgNPs for potential applications in combating oxidative stress-related disorders and promoting overall well-being (Mohanta et al. 2017b).

Study limitations

Given that our study relied entirely on Scopus to retrieve pertinent documents, it is crucial to acknowledge that substantial research on AgNPs and green synthesis might be published in journals not indexed by Scopus. Along with that, a restricted number of papers from the year 2022 may not have been integrated into Scopus during our research, likely resulting in their exclusion from our analysis. Moreover, our search disregarded items that were still in the "in press" stage. Hence, it is probable that specific review papers or research articles on the topic, published in late 2022, have been neglected due to these circumstances. Another downside of our investigation is that we exclusively adopted papers written in the English language. Research conducted in other languages may offer academics important findings into the green synthesis

of AgNPs. Lastly, it is crucial to point out that even minor inaccuracies in the names or affiliations of the authors may substantially influence the outcomes of the study.

Conclusion

In conclusion, our comprehensive bibliometric analysis illuminates the tremendous prospects of green-synthesized AgNPs across numerous scientific fields. Our investigation into future research possibilities and the current state of the field underlines the revolutionary impact of AgNPs. The potential usage of green-synthesized AgNPs in cancer detection and treatment has attracted a crucial focus, presenting the promising possibility of improved patient outcomes with diminished adverse effects. Furthermore, the eco-friendly production of AgNPs aligns with the growing emphasis on sustainability, providing a responsible approach to generating nanoparticles with remarkable anticancer activity.

In essence, this bibliometric analysis not only highlights the current achievements in the green synthesis of AgNPs but also underscores the importance of continued research, collaboration, and translation into clinical applications. The future of AgNPs holds great promise in reshaping the landscape of science and technology, ultimately benefiting society through innovative solutions in healthcare, environmental science, and beyond.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statements

The authors declared that no clinical trials were used in the present study.
The authors declared that no experiments on humans or human tissues were performed for the present study.
The authors declared that no informed consent was obtained from the humans, donors or donors' representatives participating in the study.
The authors declared that no experiments on animals were performed for the present study.
The authors declared that no commercially available immortalised human and animal cell lines were used in the present study.

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Author contributions

IH and YB: Conceptualization. SA: Methodology. IH and YB. Formal analysis. WH. Investigation. ST. Data curation MAO. All authors have significantly contributed to the development and writing of this manuscript and have read, reviewed, and approved the final manuscript.

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Data availability

All data generated or analyzed during this study are encompassed in the submitted article.

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