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REVIEW ARTICLE

Global mapping of research trends on antibacterial activity of green silver nanoparticles

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Abstract

Over the years, the quest for antibacterial agents from green nanoparticles has attracted great attention due to the global rise in the prevalence of multi-drug resistant bacteria. Although several studies on the antibacterial activity of plant-mediated silver nanoparticles have been documented, no bibliometric studies on the subject have been reported to date. As a result, the present study aimed to assess the global research trends on the antibacterial activity of green silver nanoparticles from 2000 to 2020. In the present study, we explored Science Citation Index Expanded (SCIE) to extract research articles written in English on the subject within the specified period. Two hundred and sixty-nine (269) eligible research articles were included in the bibliometric analysis and R-package "bibliometrix" was used to analyse the documents for annual scientific publications, authors' impact, most relevant institutions, countries productivity, frequent words, co-occurrence network, co-citation network and authors/institutions/countries collaboration networks. Based on the analysis, the top three (3) authors, journals, institutions and countries were Kumar V (n = 5), Zangeneh MM (n = 5) and Oh BT (n = 4); King Saud University, Banaras Hindu University and Islamic Azad University; Journal of Cluster Science (n = 10), Applied Organometallic Chemistry (n = 8) and Microbial Pathogenesis (n = 8); India, Iran, and Korea. The study findings highlighted the gaps in a research collaboration that negate productivity. Therefore, we are optimitic that this study would enlighten researchers in the field about the research lapses and the need for research collaboration in future studies.

Keywords

Bibliometric analysis, scientific productivity, green silver nanoparticles, antibacterial activity

Introduction

Metal nanoparticles are among the groups of nanomaterials that have been widely considered lately due to their exceptional physicochemical properties and various applications (1, 2). The uses of the nanomaterials cut across several fields (3). Nanomaterials are particles that are in nanoscale size (1 - 100 nm), and they are very small particles with enhanced catalytic, thermal conductivity, reactivity, chemical stability nonlinear optical performance due to their large surface area-to-volume ratio (1, 4). These salient characteristics have appealed to many researchers in the field to search for novel methods for their synthesis (5-7). Different physical and chemical methods such as hydrothermal method, physical-vapor deposition, electrochemical

changes, laser ablation, microwave technique, flame pyrolysis, photochemical reduction, spray pyrolysis, solvothermal, chemical reduction, sol-gel methods are commonly employed for the preparation and stabilization of metallic nanoparticles (8-12). High energy and pressure are required for physical methods and these made them too expensive while the chemical methods involved the use of expensive and toxic chemicals and these adverse effects have restricted their usage (9, 13-15).

Green nanotechnology is an emerging area in nanoscience due to the demand for a novel and effective approach for their synthesis (16). Although, physical and chemical methods of synthesis of metal nanoparticles can produce small-sized and well-defined particles; however, the adverse effects associated with the use of these procedures have shifted the attention of researchers to the use of biological agents (17). These biological substrates are known to be innocuous, a propitious and promising alternative to conventional methods of synthesis (18, 19). Among these biological agents, the use of extracts of plant materials has been acknowledged as the simplest and fastest preference for metal nanoparticle synthesis (20, 21). Besides being simple, this method is efficient and offers good reproducibility. In phytofabricated nanoparticle synthesis, particle properties such as size and shape are easily manipulated by changing salt concentrations, the volume of extracts, temperature, pH and time of exposure (16). In addition, the low cytotoxic activity of the metals nanoparticles has enhanced their applicability in medicine (22, 23).

Silver nanoparticles are the most widely used nanomaterials for different industrial and medical applications (24, 25). They possessed numerous unique features including but not limited to optical, electrical, antimicrobial, diamagnetic and thermal properties and these make them valuable for different applications (26, 27). Several researchers have reported on the synthesis of silver nanoparticles with antibacterial activity in the literature. For example, *Skimmia laureola* (28), *Rumex hymenosepalus* (29), *Myrtus communis* (30), *Parkia speciosa* (31), *Holoptelea integrifolia* (32), *Oedera genistifolia* (33), *Vitis labrusca* (34) and *Muntingia calabura* (35) have been explored for green synthesis. To understand the level of research progress in this field, there is a need to carry out a bibliometric analysis to grasp the holistic research trends on the subject that can provide new perspectives for future research.

Bibliometric analysis is an important statistical tool that quantitatively evaluates the scientific contribution of an author, institution and country in a particular field over the years (36, 37). The bibliometric analysis offers a quantitative review of literature in any field of research based on the citation frequency of the published research (38, 39). It is a statistical gauge that can measure the influence of research outputs within a particular subject or research field that represents the research hot spots and trends (40). As highlighted in the report (41), bibliometric analyses decrease the intrinsic bias of narrative and systematic assessments. The thrust areas of the past research in a speciality can be identified by analyzing the most-cited work currently and the information can then be used to channel future research (42). It was noted that "literature on bibliometric studies has expanded beyond the level of publication analysis and that many communities have yet to utilize them as a strategy for gathering information that could be useful in understanding the patterns and trends in their local science" (43). Bibliometric analysis has been explored on different subjects such as bioflocculant (44), diabetes (45), *Moringa oleifera* (46), HIV (47), Malaria (48), comorbidity of cancer and pain (49) etc.

Considering the proliferation of literature on the subject under study, it was most appropriate that we conducted a bibliographical review based on the available experimental bibliometric data to determine the most prominent research scholars, institutions, countries in the field (41). Therefore, in the present study, a bibliometric analysis of global research trends on the antibacterial activity of plant-mediated silver nanoparticles was evaluated to assess the research performance of authors, journals, institutions and countries. In addition, citations analysis and research collaboration networks were investigated as well as the frequent keywords used in the field to determine the future direction of the research. Therefore, the significance of this study is to integrate and provide an organized summary of the existing research by identifying the foundational studies to build knowledge, gain an understanding, and show the future direction in this research area.

Materials and Methods

Data retrieval

The Web of Science was explored to extract published research articles on the antibacterial activity of green silver nanoparticles. The search queries were (*green silver nanoparticles* AND *antibacterial*) and we focused only on research articles published on the subject study especially those indexed in Science Citation Index-Expanded (SCIE). About 293 published articles on the subject were retrieved from the Web of Science (WoS) database from 2000 to 2020. WoS is among the oldest, reliable and comprehensive databases to retrieve published documents that could be used for bibliometric studies (50). From our search, we specialized in research articles written in English and we excluded some other documents such as early access or proceedings paper or book chapter, and we obtained 269 research articles. Subsequently, these articles were downloaded in plain files format and thereafter saved in a notepad before analyses.

Data analysis

The bibliometric analysis was carried out on the R-package bibliometrix (51). The tool is designed for quantitative research in scientometrics and bibliometrics and it provides several routines for analysis and supports all the crucial steps of a classical bibliometric workflow (41). Retrieved data in plain text was uploaded in Biblioshiny on Rstudio software (v.3.4.1) to analyse the annual scientific production, authors' impact, institutions and countries research

outputs, funding agencies, relevant journals, most cited papers, keywords, historical direct citation network, co-citation network authors/institution/countries collaboration networks.

Results and Discussion

The research trends in antibacterial activity of green silver nanoparticles research were carried out in the present study and we explored WoS as a source of the information for the bibliometric analysis (52). Given the global recognition of English, we only focused on those research articles written in English and excluded others that were written in other languages (53). However, the Web of Science Core Collection is not designed for bibliometric studies, but it can be explored for finding literature (54). Therefore, it is important for researchers to use SCI-EXPANDED with the accurate bibliometric method (55). As highlighted, Web of Science was explored as a target database due to the fact it is one of the oldest databases to extract research publications for different analyses and it has citation metrics from 1945 to the present (56). SCI-Expanded is the most important database for an overview of scientific production (57).

In the present study, Table 1 depicts vital information about the research trends of research on green silver nanoparticles with antibacterial activity from 2000 to 2020. About 1158 authors wrote the 269 research articles extracted from SCI-Expanded. They comprise 710 keywords with 6796 references. The average years from the publication were 3.27, average citations per document and average citations per year per document were found to be 26.47 and 5.167, respectively. We found that authors appearance to be 1320, authors of single-authored documents and authors of multi-authored documents to be 7 and 1151, respectively. The author's collaboration in the research field was also analysed and we found single-authored documents, documents per author, authors per document co-authors per documents, collaboration index to be 7, 0.232, 4.3, 4.91 and 4.39, respectively.

Table 1. Main information about Data.

Description	Results
"Timespan"	2010-2020
"Sources (journals)"	135
"Documents"	269
"Average years from publication"	3.27
"Average citations per documents"	26.47
"Average citations per year per doc"	5.167
"References"	6796
"**Document types**"	
"Article"	269
"**Document contents"**	
"Keywords plus (id)"	513
"Author's keywords (de)"	710
"**Authors"**	
"Authors"	1158
"Author appearances"	1320
"Authors of single-authored documents"	7
"Authors of multi-authored documents"	1151
"**Authors collaboration**"	
"Single-authored documents"	7
"Documents per author"	0.232
"Authors per document"	4.3
"Co-authors per documents"	4.91
"Collaboration index"	4.39

Annual scientific production

Research outputs have been connected to the intellectual wealth and economic progress of authors or institutions or countries (58). Research outputs are usually disseminated through academic publications. The most commonly used indicator to measure research outputs is the publication of articles in indexed databases (59, 60). In the present study, the immense growth in research outputs on the topic has been documented and its collection in bibliographic databases has resulted in the exploration of bibliometric as a suitable means to measure the research activity based on the statistical analysis of quantitative data in the literature (41). In this study, the annual distribution of research outputs on the subject from 2010 to 2020 in SCI-EXPANDED are represented in Fig. 1. A total of 269 research articles were published in the Web of Science database over this period. We observed low productivity from 2010 to 2012 (n =11) and a gradual increase in research output was noticed in the subsequent year with a maximum of 55 articles recorded in 2019. Over 78.4% (211/269) of the documents were published between 2015 and 2019. Results showed that this research has drawn wide concern, and the number of published articles has continued to increase rapidly over the past two decades (61). The increase in the research outputs in the field over the year might be due to several factors, which include an increase in research grants, an increase in the research interest of more researchers in the field, acquisition of new instruments, authors and institution collaborative networks among others (45, 53).

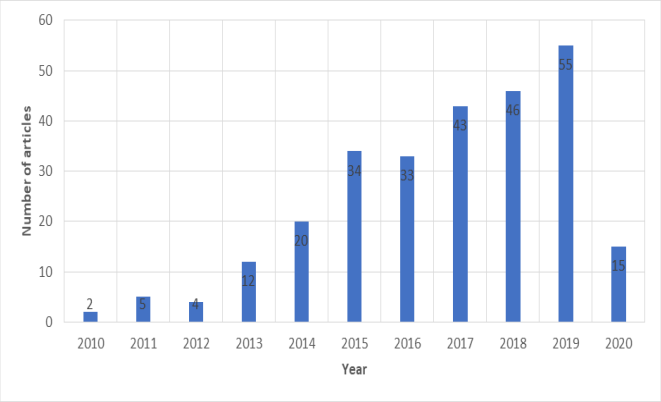

Fig. 1. Annual scientific production of antibacterial activity of green silver nanoparticles.

Most relevant authors

This section revealed the most relevant authors, established by the number of articles published on the subject within the specified period by the researchers in the field

(Table 2 and Fig. 2). Both Kumar V and Zangeneh MM crowned the list with 5 articles each followed by Oh BT, Krishnaraj C, Iravani S and Shameli K (Supplementary Fig. S1). In terms of authors' impact, the h-index was used as an in-

Table 2. Most relevant authors on antibacterial activity of green silver nanoparticles.

Top 20 productive authors				Top 20 impactful authors						
Authors	**Articles**	**Authors-Frac**	**Articles Fractionalized**	**Author**	**h_index**	**g_index**	**m_index**	**TC**	**NP**	**PY_start**
Kumar V	5	Zangeneh MM	1,8167	Zangeneh MM	3	3	1,5	82	3	2019
Zangeneh MM	5	Arunachalam J	1,3333	Zangeneh A	2	2	1	56	2	2019
Oh BT	4	Patra JK	1,3333	Karishma S	1	1	0,5	3	2	2019
Samrot AV	4	Ruiz-baltazar AD	1,2	Keerthana D	1	1	0,5	3	2	2019
Veisi H	4	Kathiravan V	1,1667	Raji P	1	1	0,5	3	2	2019
Arokiyaraj S	3	Al-ogaidi IAZ	1	Samrot AV	1	1	0,5	3	2	2019
Arunachalam J	3	Chumpol J	1	Aadil KR	1	1	0,5	5	1	2019
Bhatti TM	3	Mehata MS	1	Ahmad R	1	1	0,5	3	1	2019
Cho M	3	Oda AM	1	Ahmed N	1	1	0,5	1	1	2019
Du J	3	Pandit R	1	Aini AN	1	1	0,5	1	1	2019
Jafarizadeh-Malmiri H	3	Siri S	1	Al Farraj DA	1	1	0,5	1	1	2019
Jalali SAH	3	Yilmaz BYB	1	Al Khulaifi MM	1	1	0,5	1	1	2019
Khan M	3	Samrot AV	0,9048	An QL	1	1	0,5	3	1	2019
Kim GD	3	Veisi H	0,8667	Anand Mav	1	1	0,5	2	1	2019
Lee SM	3	Kumar V	0,8345	Araujo MC	1	1	0,5	14	1	2019
Mandal AK	3	Kora AJ	0,8333	Arulmozhi M	1	1	0,5	7	1	2019
Mehmood A	3	Singh H	0,8333	Aulla SM	1	1	0,5	1	1	2019
Murtaza G	3	Du J	0,8095	Azeem M	1	1	0,5	3	1	2019
Pandian K	3	Jalali SAH	0,7833	Bahabadi SE	1	1	0,5	17	1	2019
Park JH	3	Bhatti TM	0,7	Bai YH	1	1	0,5	5	1	2019

TC- total citations, NP – number of publication, , PY – publication year

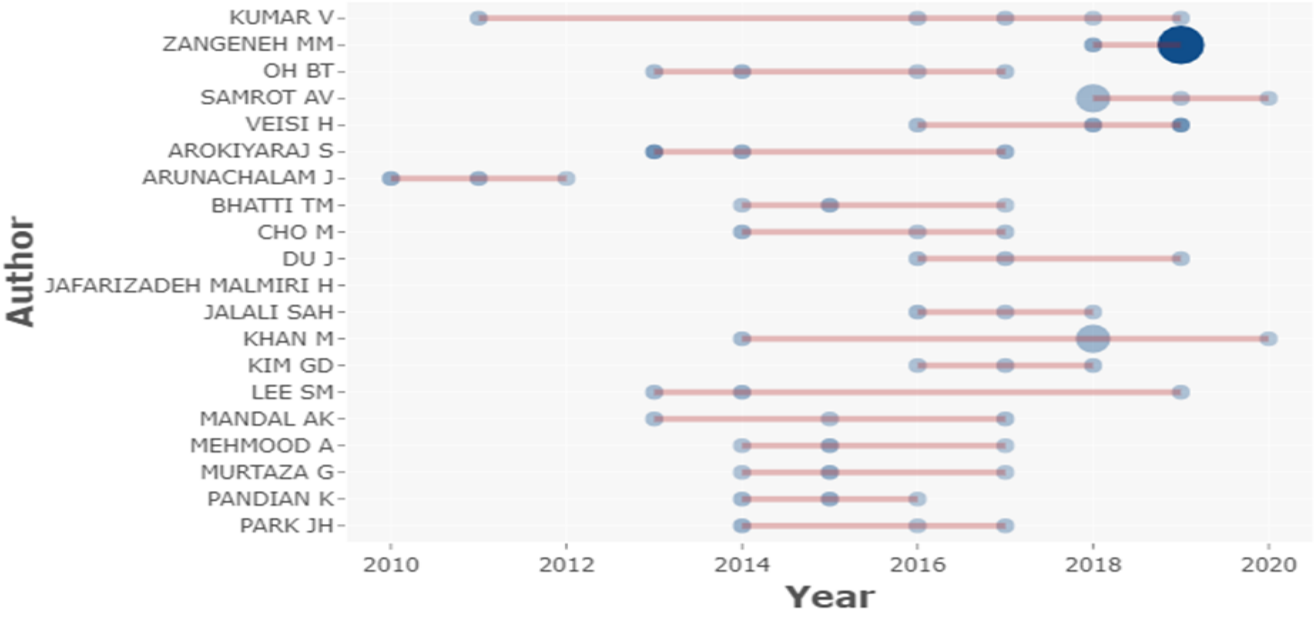

Fig. 2. Authors' productivity on antibacterial activity of green silver nanoparticles.

Samrot AV and Veisi H with 4 each. In terms of authors-fraction, Zangeneh MM has articles fractionalized value of 1.8167 followed by Arunachalam J and Patra JK with 1.3333. In terms of the number of articles published on the subject, Kumar V (n = 5) was the most relevant author, but the most cited author was Shankar SS with 95 citations. The 10 topmost cited references on the subject include Shankar SS, Philip D, Sharma VK, Ahmed S, Rai M, Morones JR, Sondi I, dicator to measure the scientific impact of authors and the results are represented in Table 2 and the most impactful author is Zangeneh MM (h-index of 3), total citation of 82 since 2019, followed by Zangeneh A (h-index of 2) with 56 citations (Supplementary Table S1). According to the reports (62, 63), "perceptions of research productivity patterns of authors differ greatly, and the productivity pattern of authors is not only subjective but also a function of an

enabling scientific environment". Lotka's Law is often called "inverse square law", "indicating that there is an inverse relationship between the number of publications and the number of authors producing these publications" (64). Connecting this law to our findings in the present study, we observed that when the number of documents was 1, the number of authors were 1034 and the proportion of the authors was 0.893 (Supplementary Table S2). As the number increases to 5, the number of authors decreased to 2 and the proportion of authors was reduced to 0.002. In terms of the authors' productivity over the year, Arokiyaraj S had total citations of 237 and a total citation per year of 29625 in 2013 followed by Arunachalam J with 155 total citations and total citations per year of 14,091 in 2010 (Supplementary Table S3). As reported (65), "the rate of citation may not reveal a researcher or nation's publishing efficiency, because the larger the number of articles used for evaluation, the greater the influence of a few frequently cited articles". Consequently, as put forward "false quality metrics could result from self-citations, citation outside WoS, citation or articles published in predatory journals and inaccurate citations" (66).

Most relevant journals and subject categories

The results depicted in Table 3 show the most relevant journals on the subject. The top five (5) journals on the subject study included Journal of Cluster Science (n = 10), Applied Organometallic Chemistry (n = 8) and Microbial Pathogenesis (n = 8), Artificial Cells Nanomedicine and Biotechnology (n = 7), Colloids and Surfaces B-Biointerfaces. Only three (3) of the five (5) top journals focused on nanotechnology. Microbial Pathogenesis specializes in biological subjects and Colloids and Surfaces B-Biointerfaces is a general journal with a wide scope of subjects. Journal of Cluster Science (h-index 39) is a springer journal with an impact factor of 2.125 (2018), active in production since 1990 and is a Chemistry discipline which fits into the subject of study and the journal is devoted to publishing research on nanoparticles and this justifies why is the most relevant journey in the study. Applied Organometallic Chemistry is a Wiley Online Library that has an impact factor of 3.259, 17/71 (Chemistry, Applied) 10/45 (Chemistry, Inorganic & Nuclear). One critical factor that influences journal productivity is ranking in the field (67).

Citation analysis involves calculating the number of times other researchers cite an article to gauge the impact of a publication or author. Papers published early gain more citations than those published in the recent time no matter the quality of the content and this means that it is improper to compare citations of papers published two decades ago with those published like a year ago. Hence, the impact of published articles is assessed after at least after 5 years of publication. As highlighted, an increase in the age of publication positively influenced the citation frequency (68). Hirsch announced the h-index in 2005 and subsequently, it became a very popular bibliometric meas-

Table 3. 20 most relevant journals on antibacterial activity of green silver nanoparticles.

Most Relevant journals			20 most global cited documents			
Sources	**Number of articles**	**Sources**	**Citations**	**Paper**	**TC**	**TC per year**
Journal of Cluster Science	10	Colloid Surface B	489	Prakash P, 2013, Colloid Surface B	237	29,625 29,625
Applied Organometallic Chemistry	8	Spectrochim Acta A	307	Jagtap UB, 2013, Ind Crop Prod	194	24,25
Microbial Pathogenesis	8	Mater Lett	209	Khalil MMH, 2014, Arab J Chem	192	27,429
Artificial Cells Nanomedicine and Biotechnology	7	J Colloid Interf Sci	193	Dhand V, 2016, Mat Sci Eng C-Mater	173	34,6
Colloids and Surfaces B-Biointerfaces	7	Colloid Surface A	191	Saxena A, 2012, Mater Lett	172	19,111
Journal of Photochemistry and Photobiology B-Biology	7	Nanotechnology	167	Sun Q, 2014, Colloid Surface A	164	23,429
Materials Letters	7	Langmuir	157	Kora AJ, 2010, Carbohyd Polym	155	14,091
Spectrochimica Acta Part A-Molecular and Biomolecular Spectroscopy	7	Int J Nanomed	144	Zargar M, 2011, Molecules	150	15
Bionanoscience	6	Nanomed Nanotechnol	142	Ravindra S, 2010, Colloid Surface A	146	13,273
Materials Science & Engineering C-Materials for Biological Applications	6	Ind Crop Prod	132	Hebeish A, 2011, Carbohyd Polym	142	14,2
RSC Advances	6	J Nanopart Res	131	Anandalakshmi K, 2016, Appl Nanosci	140	28
Applied Nanoscience	5	Carbohyd Polym	127	Reddy NJ, 2014, Mat Sci Eng C-Mater	140	20
Bioprocess and Biosystems Engineering	5	Dig J Nanomater Bios	121	Dinesh D, 2015, Parasitol Res	136	22,667
Carbohydrate Polymers	5	Mat Sci Eng C Mater	117	Shameli K, 2012, Chem Cent J	132	14,667
Green Chemistry Letters and Reviews	5	J Phys Chem B	110	Bindhu MR, 2015, Spectrochim Acta A	129	21,5
IET Nanobiotechnology	5	Appl Nanosci	107	Venkatpurwar V, 2011, Mater Lett	115	11,5

Research on Chemical Intermediates	5	J Photoch hotobio B	97	Rastogi L, 2011, Mater Chem Phys	114	11,4
Arabian Journal of Chemistry	4	J Am Chem Soc	94	Arokiyaraj S, 2014, Int J Nanomed	97	13,857
International Journal of Biological Macromolecules	4	Green Chem	86	Das J, 2013, Spectrochim Acta A	91	11,375
Journal of Nanoscience and Nanotechnology	4	RSC Adv	86	Mariselvam R, 2014, Spectrochim Acta A	90	12,857

ure (69). According to one report, "H-index is one specific method using citation analysis to determine an individual impact" (70). An individual's h-index usually vary in different databases and this could be to the fact that databases index different journals and cover different years. For instance, Scopus only have records of published papers from 1996 or later, while the Web of Science calculates an h-index using all years that an institution has subscribed to it.

The 269 research articles on the subject were distributed in 25 Web of Science subject categories (Supplementary Table S4). A total of 54 articles were published by Chemistry Multidisciplinary followed by Materials Science Multidisciplinary (n = 39), Nanoscience Nanotechnology (n = 39), Materials Science Biomaterials (n = 31), Biotechnology Applied Microbiology (n = 29), Chemistry Inorganic Nuclear (n = 21), Chemistry Applied (n = 19), Chemistry Physical (n = 19), Engineering Chemical (n = 19), Biochemistry Molecular Biology (18). This points out a big issue that comprises a huge separation between journals related to specific sectors and those that are more general. As underlined by relevant scholars, industry-specific and empirical papers should foster theoretical and general concepts in the field. It is also because authors who write in general journals often neglect reading articles in more specific but likewise important top journals, even if they are more-sector specific. The most cited journal on the subject study in these 269 articles was Colloid Surface B with 489 citations followed by Spectrochim Acta A, Mater Lett, J Colloid Interf Sci, Colloid Surface A with 307 and 209, 193 and 191 respectively (Table 3).

According to Bradford's law, which states, "that Bradford's law was not useful for predicting the size of the literature on a subject from the number of articles appearing in core journals" (71). As described (72), "Bradford's Law of Scattering is a law of diminishing returns and scattering. Bradford formulated the law in 1948 and claimed that for a given subject area, there are a few very productive periodicals, a larger number of more moderate producers, and a still larger number of constantly diminishing productivity''. Researchers have defined a subject area in lexical, semantic and subject scattering terms (73), and some argue that problems in defining ''subject'' may not matter, provided it is applied consistently (74). Relating Bradford's law to our findings in the present study, we found that out of the 20 top journals (Supplementary S5), the first thirteen journals belong to zone 1, which implies that they are the most cited journals on the subject under study whereas, the remaining journals classified under zone 2 (middle third) have an average amount of citations (75). Bradford's model may reflect the highly interdisciplinary nature of the antibacterial activity of silver nanoparticle research.

According to one report (71), this law has been applied successfully to measure the literature of many subjects. The frequently cited articles may be assumed to have been more useful than publications that are rarely cited or not at all and be more useful and thus important in their own right (76). This means that the number of citations may be considered as a measure of the article's usefulness, impact, or influence on another research. The same perceptive can be used for aggregated levels of articles. This is the typical way of justifying the use of citations as a performance indicator. Recently, the connection between scholarly quality and citations has become more intricate as researchers have realized the need to increase their visibility. This has become urgent as research funding has become scarce and the competition for resources has sharpened. In addition, since the use of citation indicators as performance indicators, researchers know that their references may influence the careers of the researchers they cite (77). The trend analysis of the influence of age of publication on the citation density showed that certain topics after reaching maturity show a decrease in citation density (68). It has been described that the real impact of a publication can only be evaluated at least two decades after it has been published (68, 78). Nevertheless, it is remarkable that with the changing trends of how published work is reviewed, the accessibility of literature has increased multi folds, and

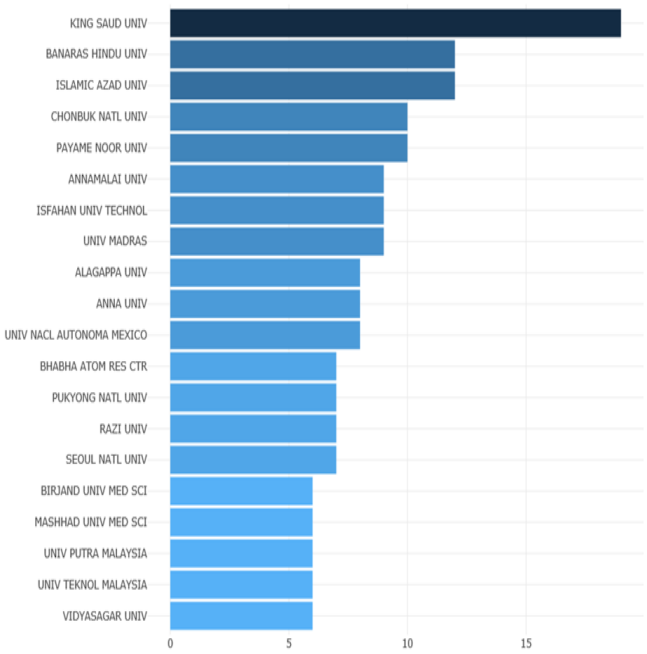

Fig. 3. Top 20 most relevant affiliation

research from around the world can be remotely reviewed without needing access to archives, libraries and published paper journals (68).

Most relevant affiliations

Based on the distribution analysis of the relevant institutions on the subject, it would be stress-free to comprehend the scientific research capabilities of each institution and their global contribution in the field and perhaps, the outputs of the corresponding authors originating from such institutions. Fig. 3 depicts the top 20 institutions on the subject and we found that King Saud Univ top the group with 19 articles, followed by Banaras Hindu Univ (12), Islamic Azad Univ (12), Chonbuk Natl Univ (10), Payame Noor Univ (10), Annamalai Univ (9), Isfahan Univ Technol (9), Univ Madras (9), Alagappa Univ (8), Anna Univ (8), Univ Nacl Autonoma Mexico (8), Bhabha Atom Res Ctr (7), Pukyong Natl Univ (7), Razi Univ (7), Seoul Natl Univ (7), Birjand Univ Med Sci (6), Mashhad Univ Med Sci (6), Univ Putra Malaysia (6), Univ Teknol Malaysia (6), Vidyasagar Univ (6). From our results, it is surprising that none of the research-based centres made it to the top 20. It could be seen that the universities dominated the field, and this could be possible since most of the researchers working at research centres are not keen on publication unlike the academics at the universities where publication is part of the criteria required for their academic promotion assessment. Secondly, in some countries such as South Africa, the amount of funding released by the government to each university is determined by their productivity, which includes the research outputs and number of postgraduates who graduated in a year. This approach promotes productivity, consequently the number of published articles. However, we are not sure whether funding in other countries is dependent on research productivity and how much of that affected research productivity among the top countries reported in this study.

Countries productivity

Based on the search queries, the top 20 most productive, most cited, and authors' countries are represented in Table 4. India is the most productive (270), most cited (3468), and top author's corresponding country (0.39033 frequency, 84 single country publication (SCP) followed by Iran (116), 858 citations, and 0.1487 frequency (33 SCP) as a contributing country on the subject (Table 4). South Korea is the third productive country (56) and cited country (632) corresponding authors' country (0.09665, 12 SCP). China is the fourth productive country (47), citation (471), and SCP (12). We found that Malaysia was the fifth productive (29), citations (346) but the fifth corresponding country is Egypt (0.02974, SCP of 5) and Malaysia is the sixth on the list for the authors' country. Concerning productivity, Asian countries were dominant in the research understudy (India, Iran, South Korea, China, Malaysia, Saudi Arabia, Thailand, Pakistan, Vietnam, Bangladesh, Iraq, Indonesia) with 3 African countries (Egypt, Nigeria and South Africa) and 2 North American countries (Mexico and USA), 2 South America (Argentina and Brazil). The productivity of the region countries could be ascribed to the fact that most of the research institutions are from Asian countries and most of the research funding agencies recorded in this study originated from these territories (Supplementary S6). Of which, the top 5 funding agencies include University Grants Commission India, Department of Science Technology India, Dean-

Table 4. Country productivity and corresponding author's country.

Country productivity		Most cited countries			Corresponding author's country					
Country	Frequency	Country	TC	AAC	Country	Articles	Freq	SCP	MCP	MCP_Ratio
India	270	India	3468	3 33,03	India	5	0,39033	84	21	0,2
Iran	116	Iran	858	21,45	Iran	40	0,1487	33	7	0,175
South Korea	56	Korea	632	24,31	Korea	26	0,09665	12	14	0,538
China	47	China	471	26,17	China	18	0,06691	12	6	0,333
Malaysia	29	Malaysia	346	43,25	Egypt	8	0,02974	5	3	0,375
Saudi Arabia	28	Egypt	227	28,38	Malaysia	8	0,02974	2	6	0,75
Thailand	17	Saudi Arabia	224	28,00	Saudi Arabia	8	0,02974	4	4	0,5
Egypt	16	USA	199	49,75	Thailand	6	0,0223	5	1	0,167
Pakistan	15	Italy	136	136,00	Mexico	5	0,01859	5	0	0
Mexico	14	Pakistan	127	25,40	Pakistan	5	0,01859	4	1	0,2
USA	14	Thailand	106	17,67	Turkey	4	0,01487	4	0	0
Nigeria	13	Brazil	65	21,67	USA	4	0,01487	3	1	0,25
Vietnam	13	Nigeria	47	23,50	Brazil	3	0,01115	2	1	0,333
Bangladesh	8	Mexico	35	7,00	Indonesia	3	0,01115	2	1	0,333
Iraq	8	Vietnam	33	11,00	Iraq	3	0,01115	3	0	0
South Africa	8	Turkey	32	8,00	South Africa	3	0,01115	3	0	0
Argentina	7	Poland	26	13,00	Vietnam	3	0,01115	3	0	0
Brazil	7	South Africa	20	6,67	Argentina	2	0,00743	2	0	0
Turkey	7	Japan	18	9,00	Japan	2	0,00743	0	2	1
Indonesia	6	Argentina	17	8,50	Nigeria	2	0,00743	1	1	0,5

Freq – frequency, SCP – single country publications, MCP – multiple country publications

ship of Scientific Research at King Saud University, National Natural Science Foundation of China and Scientific Industrial Research CSIR India. From our findings, we could observe that Asian countries were more committed to funding research in this research understudy than other continents, and this accounts for the reason why most of the corresponding authors are from Asia. One of the most influential factors that drive research is funding. Besides, a country that value the importance of research will support it because sophisticated laboratory instruments and reagents are very expensive. The absence of funding hinders research progress and discourage researchers. However, the availability of funding on the subject assisted the researchers in Asia as compared to other developing countries in Africa where research funding is lacking and the researchers tend to use their personal money to purchase equipment and reagents to carry out research. As a result, researchers' potentials or skills are hampered and consequently affects the quality of research output.

Three-Fields plot (Keywords connection with authors and institutions)

Keywords are important strategy for searching published documents in the literature (79). It is the cornerstones of the discoverability of any manuscript and therefore, quality journals and publishers should mandate the inclusion of keywords in every publication to ensure maximum visibility of the publication across all databases (68). A research hotspot refers to a focus of research for which scholars have explored severally for publication. By computing, the frequencies and relationships of words reflecting the content of articles that appear in a field, the hotspots of the field can usually be identified (80). Keywords are the essence of academic papers (81), through the analysis of high - frequency keywords (40), the overall characteristics and development trends of the field can be revealed (13), and research hotspots in this field are able to be obtained more efficiently (82).

It is highly important that researchers familiarize themselves with some specific terms used in a particular field they are interested in if not, searching for valuable documents will be difficult (83). Keywords are the keystones of the discoverability of any paper and hence, reputable publishers and journals should make compulsory the use of at least 5 keywords in a manuscript submission (84). The presence of keywords in an article increases the visibility and reflectiveness of the article across all databases (68). However, keywords were not mandatorily for articles published before 1995 and the visibility of those articles are very poor. During manuscript submission, because authors are obliged to fill the keywords section on the journal's website whereas the keywords might not be part of the original manuscript being submitted. Consequently, this irregularity hampered keyword analysis when searching for such published articles (85).

Author keywords could identify the central emphasis of a research article and pinpoint a certain pattern of the research based on analysing the most frequent keywords. The bibliometric analysis through author keywords has been proved to be an effective method in revealing the scientific research trends and hotspots (39). The most frequently used keywords in the field are represented in Fig 4a. In the same vein, Fig. 4a reveals the connection between the most frequently used keywords in this subject with key authors and most productive countries. We observed that Indian researchers have exploited most of the keywords in their published papers on the subject followed by Iran and Korea. Similarly, the 20 topmost occurrence terms in all the articles on the subject are regarded as the present research hotspots in the field. For example, the word "biosynthesis" was recorded 108 times, "leaf extract" was 68 times, "extract" appeared 42 times and "antimicrobial" was recorded 37 times (Supplementary Fig. S2).

Co-citations network

The results of the co-citation network of the top 22 authors related to the subject study are represented in Fig. 5. Each node in the sphere grid indicates different authors and the diameter of the node relates to the co-citation rate with other researchers in the field, and lines illustrate the co-citation network among the authors. The age of a paper influences its citation over the year. From this study, we observed that Sharma VK, Morones Jr, Shankar SS, Krishnaraj C and Sondi were the top 5 with a high co-citation rate and these authors interconnect with themselves (Fig. 5). Papers published 10 years ago will have more citations more than those published a year ago (86). This accounts for why recently published papers do not appear in the results presented in this section (Fig. 5). Most other similar analyses have been used for bibliometric analysis by several researchers in different studies (53, 66).

Co-occurrence of keywords and trend topics over the years

Supplementary Fig. S2 reveals the co-occurrence of keywords on the subject study. The most frequent words used was biosynthesis and it was recorded 108 in the study, followed by leaf extract (68), extract (42), antimicrobial activity (37), reduction (31 times), Escherichia coli (29), Ag (25), antioxidant (24), metal nanoparticles (24), particles (19), ions (16), leaves (16), size (16), optical properties (15), plant (15), bacteria (13), toxicity (13). In addition, Fig. 6 depicts trend topics on the subject study over the years. To understand the green synthesis of metallic nanoparticles, some topics have been chosen as the focus of active research in the field. Between 2014 and 2016, the trend topics were growth, plant, toxicity, rapid synthesis, model, gold, *Escherichia coli*, Ag, particles, au and ions. Subsequently, between 2016 to 2020, the hotspot topics for research were biosynthesis, leaf extract, gold nanoparticles, extract, antimicrobial activity, reduction, metal nanoparticles, antioxidant, leaves, cytotoxicity, degradation, anticancer, 4-nitrophenol, oxide nanoparticles and mechanism. The rate at which the word "biosynthesis" was frequently used in 2017 followed by leaf extract. Recently, researchers in this field have diverted their attention to areas such as cytotoxicity, degradation, anticancer and their possible mechanisms of action. Potential applications of metal nanoparticles especially silver and gold nanoparticles such as catalyt-

ic, biomedical, bioremediation of green metallic nanoparticles have been extensively reported in the literature (87, 88).

quality and resources and this has been encouraged by most funding agencies because research individualism hampers progress and quality outputs (45, 89).

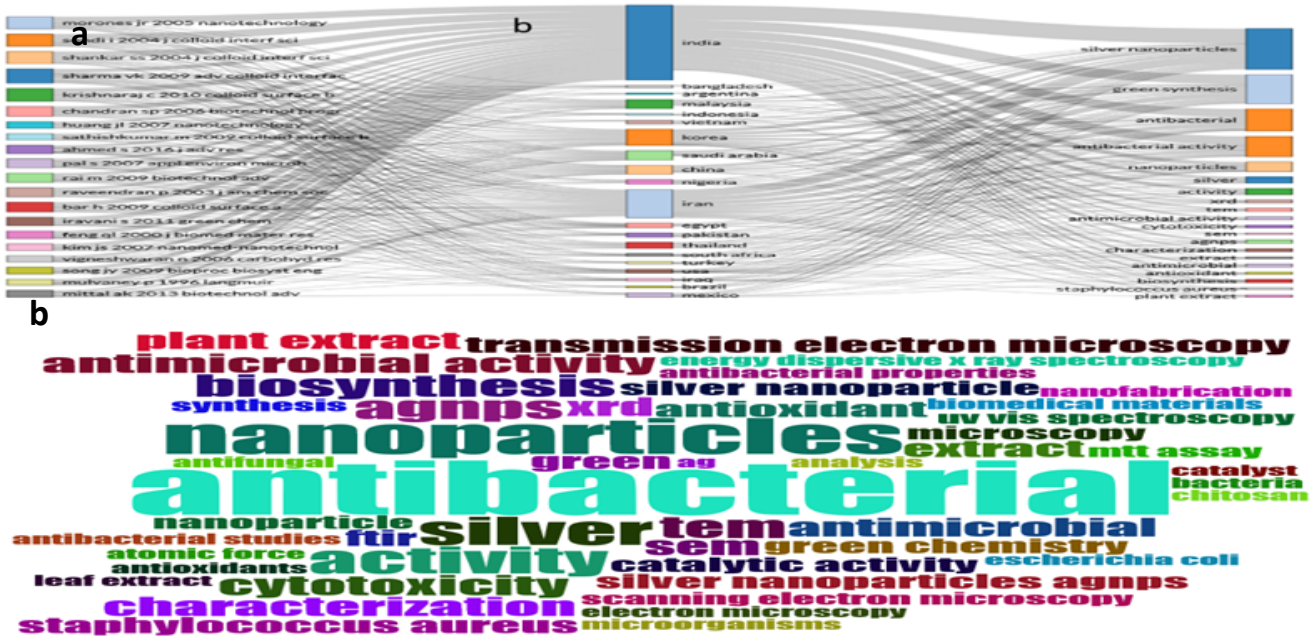

Fig. 4. Keywords connection with authors and institutions (a) and frequent words (b) used on antibacterial activity of green silver nanoparticles.

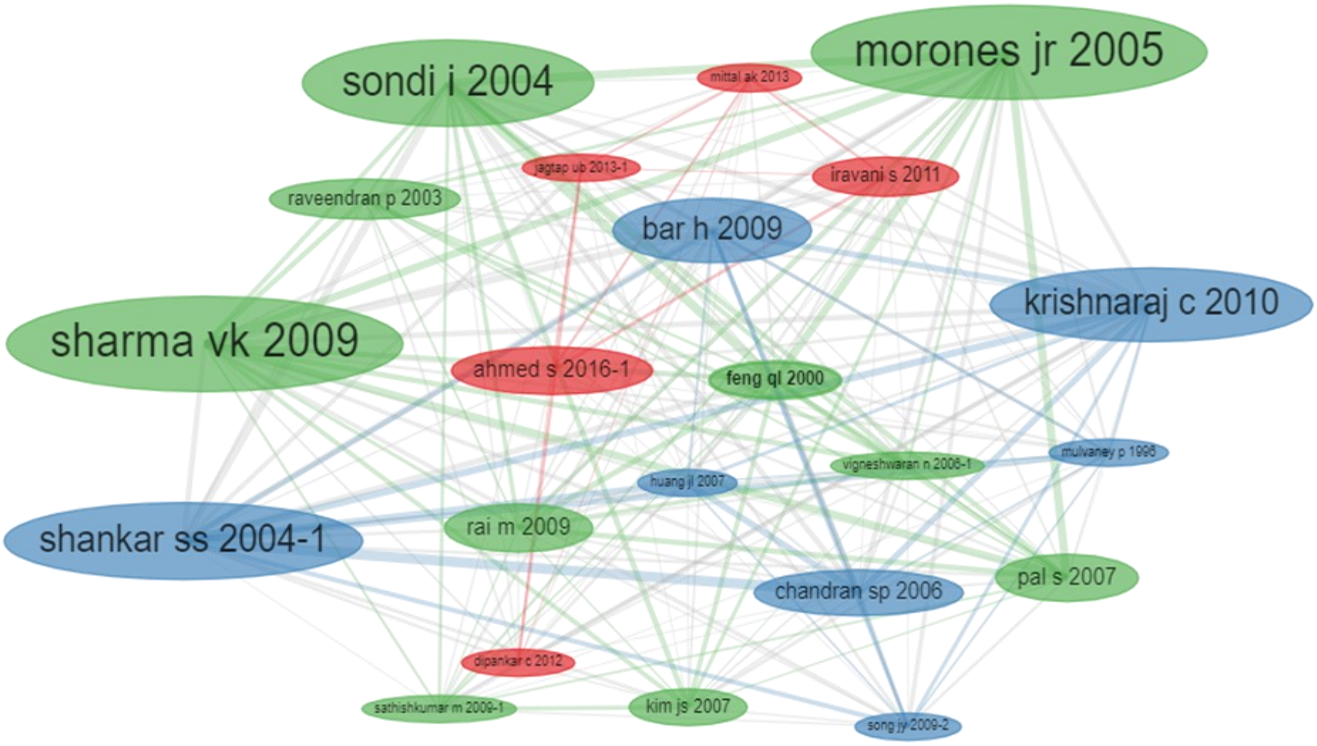

Fig. 5. Co-citation network on antibacterial activity of green silver nanoparticles.

Authors, institutions and countries collaboration network

This section displays the collaboration network among the researchers in the field study. From the results represented in Fig. 7a, we observed a strong research collaboration network between some authors and this initiative increased their research outputs significantly such that it accounted for the productivity of their respective institutions and countries. Research collaboration improves productivity,

The analysis of institutional collaboration networks on the subject is depicted in Fig 7b. We observed that some institutions have a collaboration network with each other whereas some do not involve in international collaboration and this critical factor adversely affected research productivity. As seen in Fig 7b, some institutions have a powerful network involving three (3) parties whereas others involved 2 parties. Research collaboration among scholars enhances the exchange of skills, experience, resources, knowledge,

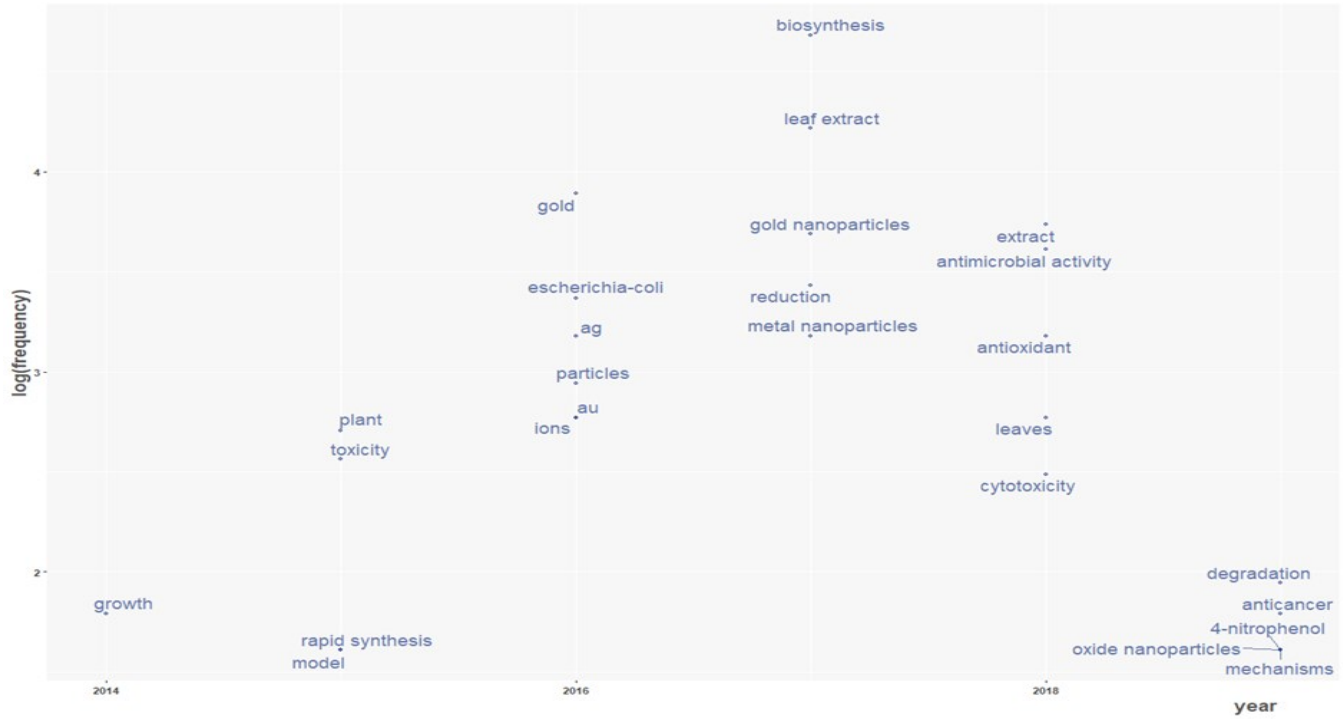

Fig. 6. Trend topics on antibacterial activity of green silver nanoparticles.

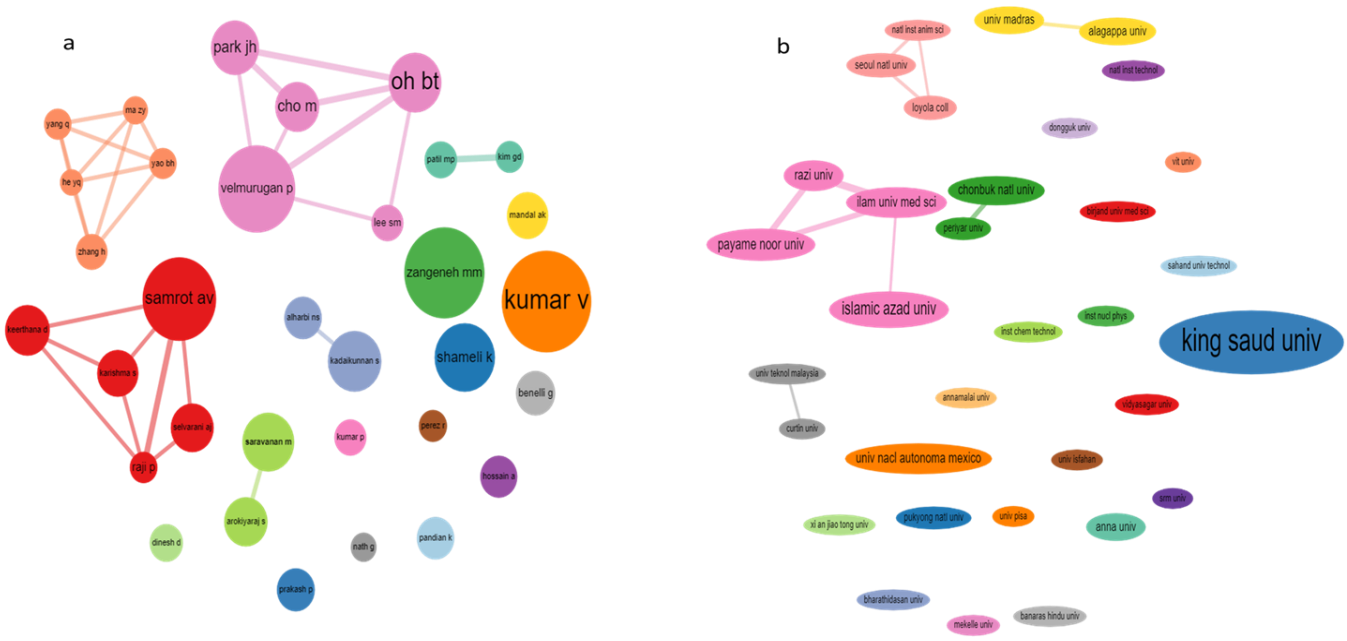

Fig. 7. Authors (a) and institutions (b) collaboration networks on antibacterial activity of green silver nanoparticles.

techniques and impactful ideas among the participants. An increase in research collaboration increases the possibilities of problem-solving. An additional advantage of working in partnership with research scholars outside your institution is the prospect to grow as an intellectual author and this will enable you to think differently contrary to when you are working only with your colleagues with a similar line of thinking (45, 46).

As represented in Fig. 8, we observed that India has a research collaboration network with Russia, Ethiopia, Saudi Arabia, United Arab Emirates, Korea, South Africa, Italy, USA and Malaysia. It is very strange to see that USA and China are not at the top of the list because they are the strongest research competitors and they are always at the top of every research. However, the low research outputs observed in specific countries could be due to a lack of collaboration networks on the subject as seen in Fig 8. Iran has a collaboration network with Malaysia, Iran, Iraq and Indonesia. Japan has a network with Bangladesh whereas other countries such as Hungary, Singapore, Brazil, Poland, Zimbabwe, China, New Zealand, Poland, Vietnam, Turkey, Norway, Jordan, Thailand, Belarus, Nigeria, Australia, Argentina, Denmark, Canada, United Kingdom, Taiwan, Ireland and Portugal do not have a research collaboration network with any country in the field and these accounts for the low productivity in these regions. The high research outputs on the subject from India and Iran could be due to the high number of corresponding authors from these territories. As highlighted by the report of Okaiyeto and Oguntibeju (45),

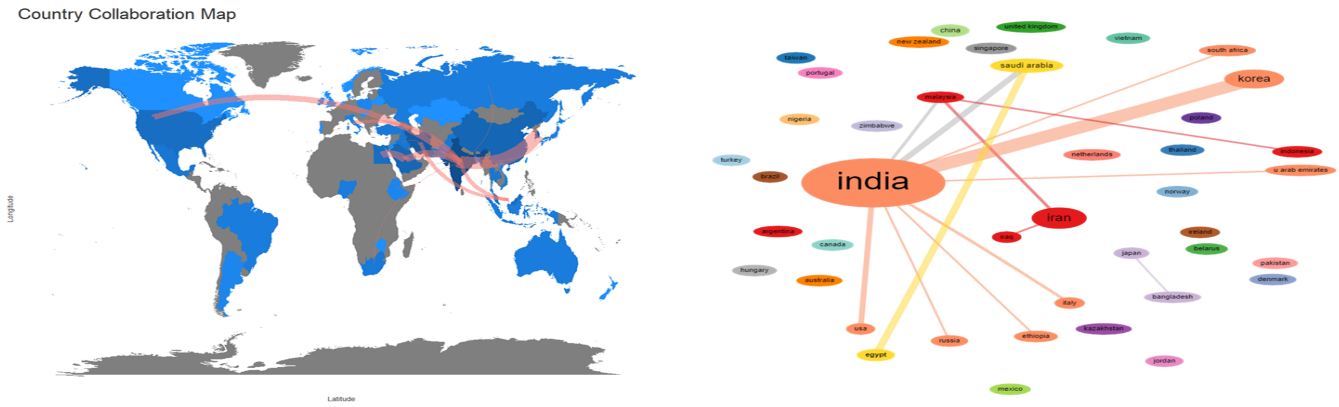

Fig. 8. Countries collaboration network on antibacterial activity of green silver nanoparticles.

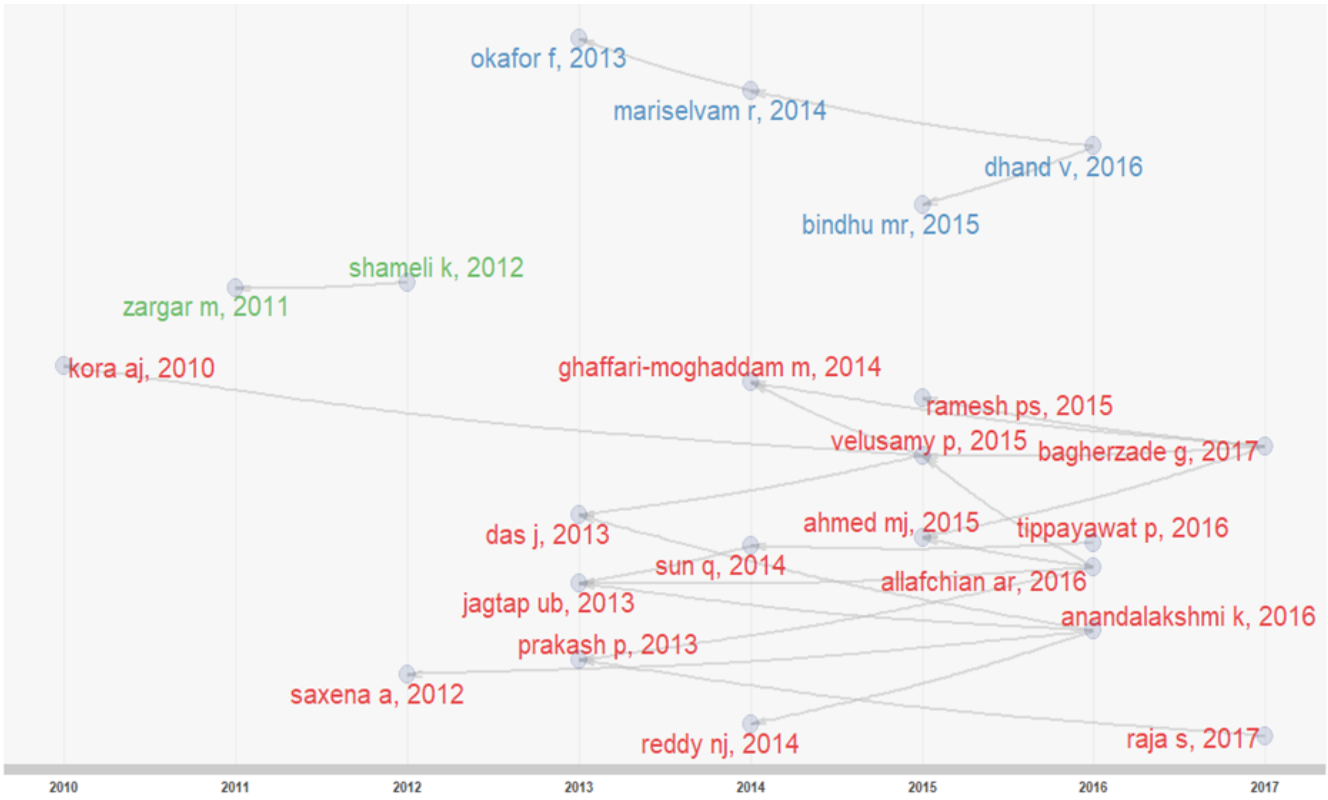

Fig. 9. Historical direct citation network on antibacterial activity of green silver nanoparticles.

international collaborations between countries provide prospects for the exchange of skills and ideas for new discoveries, division of labour and resources, key strategies to solve significant logical questions in a particular field.

Historical direct citation network

A historical direct citation network that deploys a chronological citation network is presented as an intellectual structure (Fig. 9). As highlighted in one report (90), it denotes a chronological map of the most significant citations subsequent from a bibliographic collection. The remarkable part of this visualization is that apart from revealing the authors' names and connections over the years, it also highlights some relevant topics on the subject, which could be useful for research scholars in the field.

Conclusion and limitations

The present bibliometric analyses revealed the global research trends on antibacterial activity of green silver nanoparticles between 2000 and 2020 which is based on the retrieved research articles from SCI-Expanded. Concerning the various analyses performed in this study, the method used to extract data from the literature and software used for analysis in this study is widely accepted. Our analyses showed that there is research progress in the field over the year and we noticed that research collaboration greatly increased productivity among the authors, institutions and countries and low research outputs among those collaborative networks. This study further identifies the impact of research funding on productivity and we hope that researchers in the field from institutions and countries with low productivity would be encouraged about the essence of research collaboration in their future studies.

Furthermore, in the present study, we identified a few limitations that might affect our bibliometric analyses in one way or the other. For example, in our search, we only consider research articles published in English, and those published in other languages are excluded in this analysis. Similarly, those published in databases other than SCI-Expanded were also excluded from the search as well as

those published documents that are not research articles. Furthermore, we used the WoS database to retrieve research articles included in the bibliometric analysis without consulting other scientific databases. Although, WoS have been acknowledged to be one of the oldest databases to retrieve information for this kind of analysis, nonetheless, the data obtained from WoS cannot holistically represent all research data on the subject study because some journals are not indexed in the WoS but indexed in other scientific databases such as Scopus, PubMed, etc. Hence, we can say that our opinion is only based on the information in WoS (SCI-Expanded) and articles.

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Authors contributions

Conceptualization, KO and OOO; resources, OOO; writing —original draft preparation, KO; writing —review and editing, KO, IOO and OOO; supervision —OOO; project administration, OOO; funding acquisition, OOO. All the authors have read and agreed to the published version of the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None.

Supplementary data

Table S1: Top 20 most impactful authors.

Table S2: Author productivity through Lotka Law.

Table S3: Author's production over time (2000 - 2020).

Table S4: Top 20 Web of Science categories of published on antibacterial activity of green silver nanoparticles.

Table S5: Bradford's Law.

Table S6: Funding agencies.

Figure S1: 20 most local cited authors.

Figure S2: Co-occurrence words used in the field.

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