Journal of Engineering and Technological Sciences

Research Paper

Emerging Technologies in the Development of Metallic and Bimetallic Nanoparticles in the Last Decade: A Scientometric Analysis

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Abstract

The development of nanotechnology and nanomaterials has had an upward surge in recent years, not only because of the type of technology but also because of the unique properties and characteristics of nanomaterials. This growth motivated us to make an analysis of emerging technologies in the development of metallic, bimetallic, and metal-oxide nanoparticles covering a period of ten years, which have had a high impact on the development of different products applied to biomedicine, electronics, agriculture, energy, plastics, etc. This research found more than one and a half million scientific papers under the keyword 'nanotechnology' in the Scopus database. This article reports a scientometric analysis where aspects such as articles with the highest number of citations, countries with the highest production, representative institutions in the field, authors and the relation of citations, correlations between them, keyword analysis, as well as the most studied topics in this field were investigated. On the other hand, the number of patents produced was reviewed in a general way. The databases Scopus, Journal Citation Report, VOSviewer, and other computer tools were used for the analysis. The results showed the United States (17.3%) and China (15.3%) as the countries with the greatest impact on studying metallic and bimetallic nanoparticles, with a high correlation between different countries. It is worth highlighting the participation of India with 10.1% and more than twice as many scientific papers as Germany; in the case of patents, the United States and China accounted for 55.3% of the total patents.

Keywords: *bibliometric; bimetallic nanoparticles; emerging technology; nanomaterials; nanoparticle/metal; Nano-Au; Nano-Ag; scientometric.*

Introduction

The field of nanotechnology has opened several opportunities in different applications, as it is a multidisciplinary field that works with properties and structures at the nanometer scale through chemical, physical, and biological routes. The development of nanomaterials in recent years has had an upward surge not only because of the type of technology but also because of the unique properties and characteristics of this type of materials compared to bulk materials [1]. From the 1990s onwards, many scientific articles in this field have been published. Using the Scopus database and starting with the keyword 'nanotechnology', approximately 1,613,664 documents were found since 1870. By the end of the 1990s, the growth of published articles exceeded one thousand documents per year, and from then on, the growth of published documents until the year 2021 exceeded 160,000 documents per year.

The study documents reflect a strong trend in different materials applied to nanotechnology. However, the advances and applications related to the use of nanoparticles (NPs) are growing considerably in different fields. In the case of agriculture, it arises from the need to produce food at lower cost, with improved technologies for the use of pesticides, with different applications, and with high efficiency [2-4] in food conservation processes [5]. In medicine, NPs play an essential role in the area of diagnosis and treatment of diseases [6], for drug delivery

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ISSN: 2337-5779
DOI: 10.5614/j.eng.technol.sci.2023.55.2.7

[6-8], in the area of odontology and cancer treatment [10] among others. In the environmental area, NPs are very useful for removing pollutants [11], metal NPs for arsenic removal, a significant issue in the India-China region [12]. In the field of energy, we find energy storage systems using nanostructured materials [13,14] among others, hydrogen production for cleaner energy [15], next-generation batteries [16], NPs applied in fuel cells, sensors, supercapacitors [17], and structures that improve efficiency [18,19], and for the improvement of dielectric systems for power transformers [20]; all of the above, without neglecting the environmental impact and the effect of these NPs on human beings in different areas.

This study reviewed the last decade's information on analyzing emerging techniques in the field of metal, bimetallic and oxide-metal nanoparticles, their applications, and development based on a scientometric study during the period from 2013 to 2022.

Methodology

The bibliometric research about NPs makes it necessary to analyze search results from databases such as Scopus. The data were collected on October 11th, 2022, using the Scopus and the Journal Citation Report software. Through keywords like 'metal nanoparticles', 'oxide-metal nanoparticles', 'bimetallic nanoparticles', and 'nano-Au-nano-Ag' about 3,600 documents were found. These publications were refined by document type and language for a total of 1,201 documents analyzed covering a period of ten years (2013-2022). The analysis methodology was based on studies by other authors [21,22].

The bibliometric study was based on a combination of keywords using logical operators AND, OR, and NOT, including title, abstract, author, and keywords, among others. Databases such as Scopus, Web of Science (WOS), Journal Citation Report (JCR), and software such as OpenRefine, VOSviewer, and Microsoft Excel were used. The analysis of keywords was developed based on their frequency and co-occurrence among authors or countries. This analysis was done using the VOSviewer software. The search query was composed of words such as: emerging AND (nanoparticle/metal OR nano-metal-oxide OR "bimetallic nanoparticles" OR "metallic nanoparticles" OR nano-Ag OR nano-Au OR nano-Cu OR nano-Al OR nano-Fe OR nano-Ti OR nano-Zn OR nano-CdSe OR nano-ZnS OR nano-CdTe OR nano-TiO_2 OR nano-Al_2O_3 OR nano-Fe_2O_3 OR nano-ZnO OR nano-CuO OR nanoparticles*), during the period from 2013 to 2022.

This article includes some impact indicators such as the SciteScore impact factor, h-index, Scimago Journal Rank (SJR), citation analysis, number of authors, degree of citation, and the most productive institutions and countries. In the case of author performance, the productivity index (PI) was used, where different levels are presented to indicate the productivity of the authors. The PI indicator is defined as the decimal logarithm of the number of articles published. When PI equals zero, they are considered a small producer (one single paper). When PI is between zero and one, they are considered a medium producer; finally, when PI is greater than or equal to one, they are considered a large producer (ten or more papers). An author's production is based on a limited number of citations; thus, the term 'key article' is used for those articles with fifty or more citations. On the other hand, the number of authors per publication and their impact were analyzed with the number of citations per year.

Results and Discussion

Article and Patents Analysis

Table 1 summarizes the most relevant data in the search for publications related to the development of metallic, bimetallic, and oxide-metal nanoparticles in the last decade. This analysis was made for the period 2013-2022 due to the accelerated growth that the field of nanotechnology and nanomaterials experienced worldwide.

Figure 1 shows the results obtained from the number of articles and patents between 2013 and 2022 (Scopus database) related to emerging in the development of metallic, bimetallic, and oxide-metal nanoparticles. It shows an upward growth in the number of articles and patents with an average annual growth rate of 13.5% and 10.0%, respectively. It is worth noting that the number of annual patents exceeded ten times the number of articles produced in almost the entire period.

DOI: 10.5614/j.eng.technol.sci.2023.55.2.7

Table 1 Summary table of information concerning trends in the development of metallic, bimetallic, and oxide-metal nanoparticles.

Descriptions	Results
Analyzed documents	1202
Period	2013-2022
Average growth in publication rate	13.5%
Keywords	13057
Average citations per document	33.5
Total citations	40321
Authors	7050
Countries	82
Documents with single authors	22
Types of documents	
Article	945
Review	256

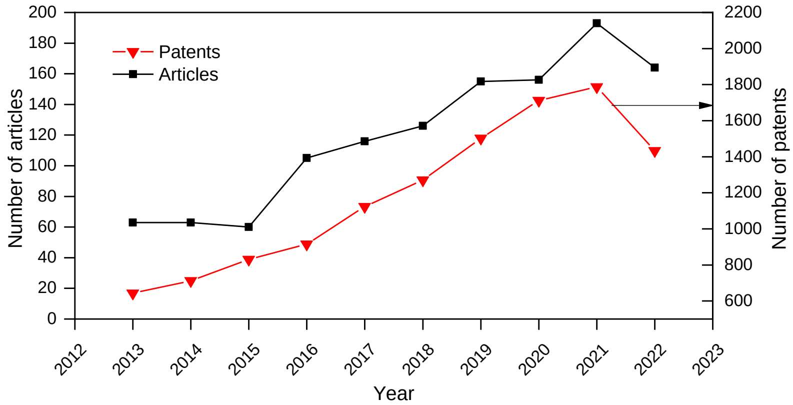

Figure 1 Timeline of publications and patents from 2013 to 2022 related to trends in the development of metal nanoparticles and others. Source: Scopus

According to WIPO (World Intellectual Property Organization), the peak generated in the year 2021 in the production of patents was due to the innovative development of companies in different sectors for the generation of new products and services in response to the Covid-19 pandemic. This demonstrates the resilience of human innovation in the face of a complex global situation.

Country Statistics

Figure 2 shows the country production analysis, considering the first 50 of the 82 countries studied. The first five countries, the United States, China, India, Germany, and the United Kingdom, accounted for 50.3% of the total documents and 81.48% of the total citations. It is remarkable to see that, apart from the three countries with the highest production, the remaining seven countries showed very similar behavior in terms of production and citations. It is interesting to note the participation of countries such as Saudi Arabia, South Korea, and Pakistan among the top-ten.

The analysis of documents and citations of the ten countries with the highest number of publications in nanoparticles, with respect to the 82 countries analyzed, is shown in Table 2. In the analysis of documents and citations of the ten countries with the highest production in the field, the United States was the country with the highest number of publications (17.3%) and citations (38.11%), followed by China with 15.53% and 23.31% in documents and citations, respectively. In general terms, it shows a high average citation rate per article. In addition, according to Scopus, it was found that out of the top-ten countries, only three had patents: the United States, China, and Canada.

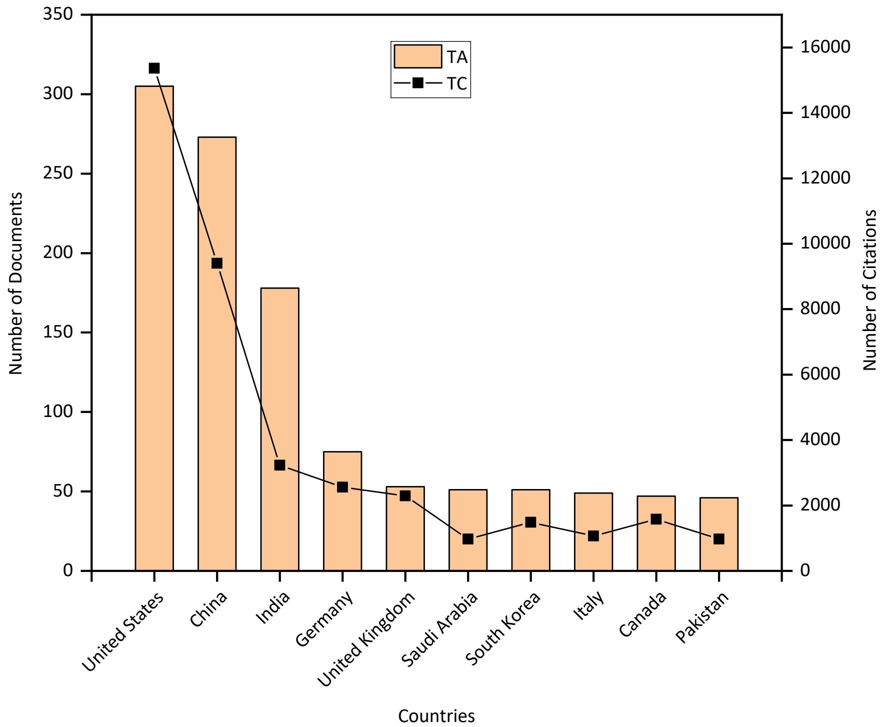

Figure 2 Geographical distribution of publications related to trends in the development of metal nanoparticles and others. Source: Scopus

Table 2 Analysis of documents and citations of the ten countries with the highest production in the area.

Countries	Total				h-index	Key Articles	
	TA	TC	TP	TAt		KA	KAC
United States	305	15366	139	1915	59	70	11437
China	273	9400	24	1821	47	41	6171
India	178	3232	0	863	33	20	1529
Germany	75	2559	0	506	22	12	1809
United Kingdom	53	2295	6	383	22	9	1655
Saudi Arabia	51	972	0	354	16	5	429
South Korea	51	1485	0	310	16	8	1044
Italy	49	1069	0	390	19	5	376
Canada	47	1576	42	297	19	8	1027
Pakistan	46	976	0	287	17	6	432

TA = total articles; TC = total citations; TP = total patents; Tat = total authors; KA = key articles; KAC = key articles citations.

Another aspect to highlight is that of the total number of articles from the first five countries, which correspond to 884 documents, 152 (17.2%) correspond to key articles (articles with more than 50 citations), with a citation rate of 56.05%. Considering the h-index and the number of citations of key articles, the United States, China, and India were the countries with the highest index, with a direct relationship with the number of publications, which is not the case in many research studies.

Countries such as India and China had a significant impact on scientific production compared to other world powers. This is because more than ten years ago, an industrial revolution process began, generated by China and India as places for low-cost manufacturing, an advantage because of which they surpassed countries such as the United States, the United Kingdom, Germany, and Japan, in terms of production. The driving force behind these processes was based on the type of product and technology used [23], hence the accelerated growth in different fields.

On the other hand, India is the second most populated country in the world and the seventh largest in size. The growing generation of scientific production is due to a series of problems in health related to the lack of products to feed the population, together with the need to generate alternatives in agriculture to solve this problem [4].

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Another case is the contamination generated by arsenic, where Bangladesh and India have been the most affected areas in recent times [12], mainly due to the exploitation of minerals and the release of this element by industries. Another pollution problem is related to the generation of rice husk, agricultural waste available in large quantities in countries such as India, China, and Bangladesh, among others. This low-value material is used to produce energy, generating waste (ashes) with high environmental impact ends up in reaches landfills or open fields [24]. These problems have made India direct research to nanotechnology and nanomaterials as alternative solutions to different problems, hence the reason for the growth in publications in this country.

Figure 3 shows the collaborative networks of 48 countries in the study of emerging in the development of metallic and bimetallic nanoparticles in the last decade. The size of the spheres represents the number of papers published by each country, the color indicates the most active period in the last ten years, and the connecting lines between them indicate the presence of cooperation.

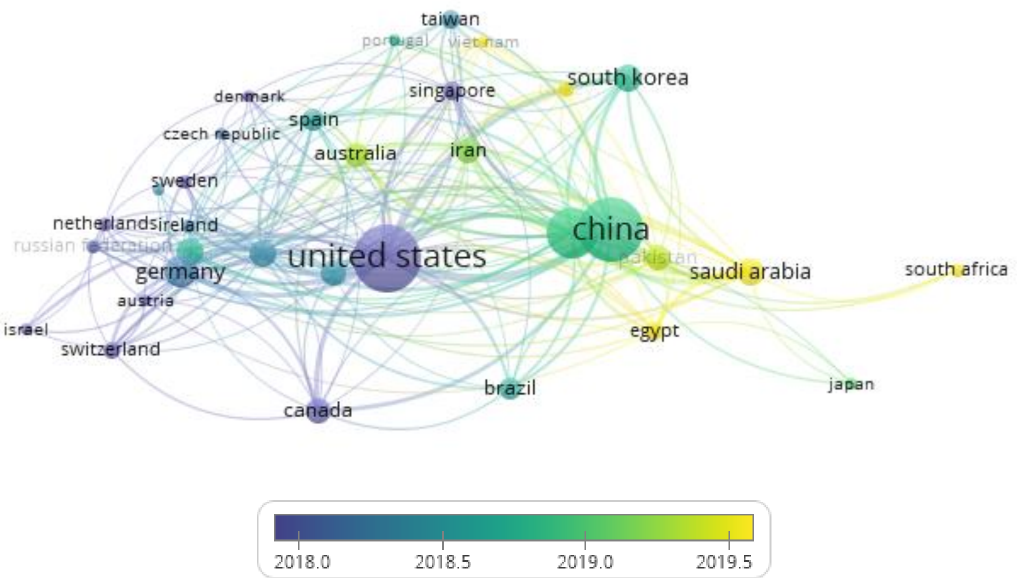

Figure 3 Collaborative networks of 48 of 85 countries in the field of emerging in the development of metal nanoparticles and others. Source: VOSviewer

The analysis using the VOSviewer software found that the United States, China, and India had total link strengths of 144, 123, and 86, respectively, with very similar numbers of links between countries.

Institutional Productions

The institutions that produced the most in the field under investigation were: Chinese Academy of Science and the Ministry of Education China. These institutions are both located in Beijing, China. Their main production fields are physics and astronomy, engineering, chemistry, and materials science. The third institute is the CNRS Centre National de la Recherche Scientifique, located in Paris, France, which works in the fields of physics and astronomy, biochemistry, and engineering, among others. The first ten institutions represent 19.2% of the total number of documents. At the production level, for all institutions in general, it was found that the institution ranking first had 16,505 patents, the second had 65 patents, and the third had 25,752 patents. This suggests that the institutions not only generate articles but also develop patents.

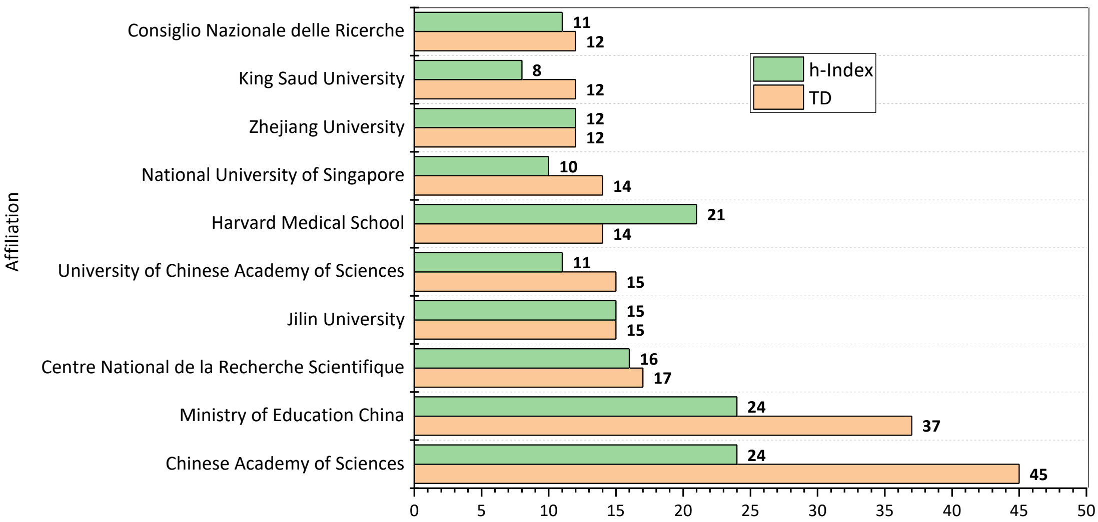

Figure 4 Distribution of the most productive institutions.

Journal Analysis

Table 3 presents the top-ten most productive journals with the most publications in the emerging field of the development of metallic and other nanoparticles in the period from 2013 to 2022. The journal ACS Nano presents the highest number of papers, with a citation percentage of 7.03% of the total number of citations. The top-ten journals with the most papers only accounted for 21.3% of total citations.

Table 3 Top-ten most productive journals in research on development of metal nanoparticles and others in the period 2013-2022.

Journal Name	Total		Relative (%)		Journal Quality			Publishing Country
	TD	TC	TD	TC	h-index	SJR	CiteScore (2021)	
ACS Nano	32	2836	4.07	7.03	413	4.61	24.3	United States
ACS Applied Materials and Interfaces	25	965	3.18	2.39	255	2.143	14.4	United States
Nanoscale	25	823	3.18	2.04	244	1.74	13.4	United Kingdom
International Journal of Nanomedicine	17	751	2.16	1.86	145	1.03	10.9	New Zealand
Scientific Reports	16	329	2.03	0.82	242	1.00	6.9	United Kingdom
Nanomaterials	15	245	1.91	0.61	80	0.84	6.6	Switzerland
Small	15	972	1.91	2.41	259	3.22	19.7	Germany
Environmental Science Nano	14	510	1.78	1.26	79	1.59	13	United Kingdom
Nano Letters	13	455	1.65	1.13	511	3.76	18	United States
Wiley Interdisciplinary Reviews Nanomedicine	13	714	1.65	1.77	80	1.62	14.9	United States

SJR = SCImago Journal Rank; TD = total documents; TC = total citations.

Of the top-ten journals, the publishing country of these corresponded to the United States with 50%, followed by the United Kingdom (30%), New Zealand (10%), and Germany (10%). However, there were no journals from countries such as China and India, countries with considerable growth in scientific production in the field of nanotechnology.

On the other hand, analyzing the journals by the degree of citation, we found that the five journals with the highest number of citations were: ACS Nano (2836), Chemical Society Reviews (2338), Nature Photonics (1896), Nature (1025), and Small (972).

Distribution by Topic

From the bibliometric study, it was found that the most representative areas in the emerging field of the development of metallic nanoparticles were materials science (17.5%), chemistry (14.1%), engineering (10.7%),

DOI: 10.5614/j.eng.technol.sci.2023.55.2.7

biochemistry and genetics (10.6%), and chemical engineering (9.9%), which corresponded to 62.7% of the total (see Figure 5).

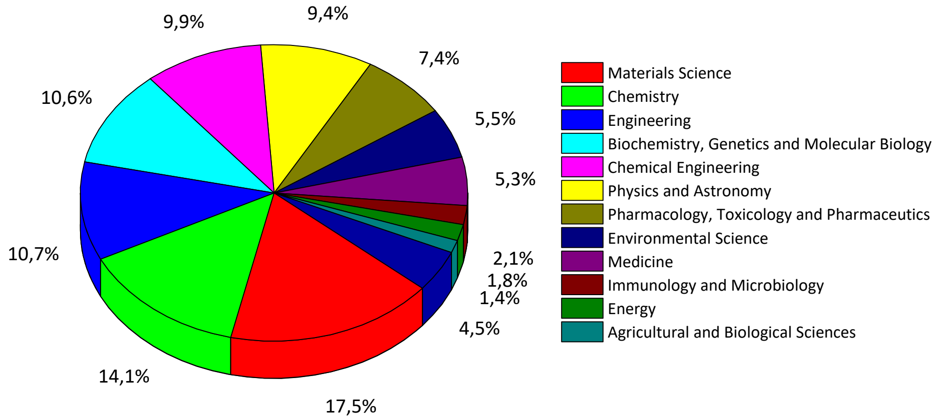

Figure 5 Distribution of publications by research areas.

Author Statistics

The 1,201 papers found in research in the emerging field of the development of metallic and other nanoparticles in the period from 2013 to 2022 were published by 7,050 authors and had 40,321 citations. Table 4 shows the top-ten authors. The author with the most papers in the area was Caracciolo, G. from Sapienza Università di Roma institute, with seven papers and 156 citations. It is worth emphasizing that Clavero, Cesar from Lawrence Berkeley National Laboratory in the United States was the author with the most citations (1896). According to the authors' production index, the ten main authors are in the medium-producing range. With h-indexes greater than 20, the author with the highest h-index was Mahmoudi, M. (83) from Michigan State University in the United States.

Table 4 Top-ten authors in the emerging field of nanoparticle development, in terms of the number of papers.

Authors	Affiliation	TA	TC	KA	h-index Topic	h-index Author	IP
Caracciolo, G.	Sapienza Università di Roma	7	146	0	6	43	0,845
Palchetti, S.	Facoltà di Farmacia e Medicina	6	115	0	5	25	0,778
Pozzi, D.	Sapienza Università di Roma,	6	115	0	5	40	0,778
Mahmoudi, M.	Michigan State University,	6	1542	3	6	83	0,778
Barcikowski, S.	Universität Duisburg-Essen, Duisburg	5	234	1	5	55	0,699
Cormode, D.P.	Philadelphia, United States	4	195	2	4	50	0,602
Dawson, K.A.	University College Dublin	4	457	4	4	80	0,602
Popovtzer, R.	Bar-Ilan University	4	131	2	4	39	0,602
Saravanan, M.	Saveetha Dental College And Hospitals	4	183	1	4	49	0,602
Digiacomo, L.	Facoltà di Farmacia e Medicina, Rome	5	86	0	5	22	0,699

Figure 6 shows the relationship between the number of authors per publication and the number of citations per year. It was found that articles with three authors represented 13.3%, with four authors 15.8%, and with five authors 13.0%, i.e., those with 3, 4, and 5 authors, they accounted for 42.1% of the total number of publications. The lowest percentage was for publications with one author (1.83%). The year 2018 was the year with the highest citation degree, i.e., 15.2% with respect to the total, followed by the years 2013 and 2014 with 15.1 and 14.8%, respectively.

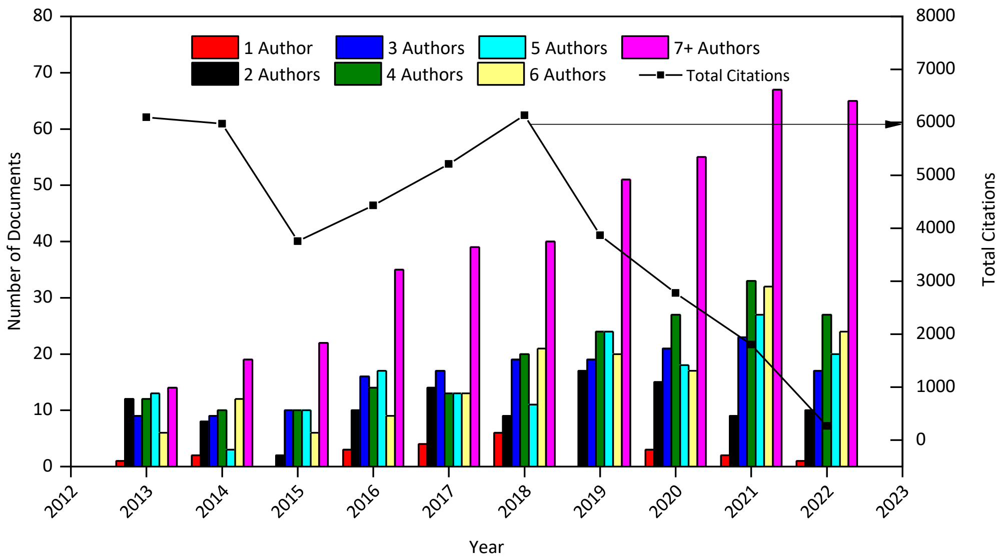

Figure 6 Number of authors per article in the emerging field of the development of metallic nanoparticles and others.

In general, publications with seven or more authors had the highest percentage (33.89%), followed by four (15.8%), and three (13.2%) authors per publication. This trend could be due to several reasons. One could be the subject matter. In this case, during the Covid-19 pandemic (2020 and 2021), many researchers united in publications with more than 40 authors. In previous years, the trend was revealed by research in the line of the treatment of deadly diseases and alternative solutions, in which the work of several institutes from the same region was observed. Another element of author participation, as is known at the research level, is given by the degree of correlation between countries, as shown in Figure 3.

Keyword Occurrence

Using the VOSviewer software, a co-occurrence analysis was performed with a minimum of 50 occurrences, where 63 unions of 13,057 keywords were obtained. Figure 7 shows a keyword correlation graph of the emerging field of developing metallic nanoparticles and bimetallic nanoparticles.

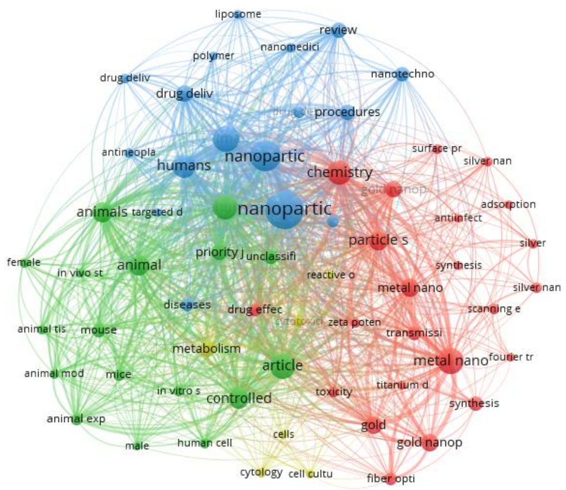

Figure 7 Keyword co-ocurrence network visualization of the research of development of metallic and other nanoparticles.

DOI: 10.5614/j.eng.technol.sci.2023.55.2.7

The size of the spheres indicates the number of documents containing each word and the colors indicates cluster formation. For the occurrence analysis, four clusters are presented, which show the following keywords. In Cluster 1, 'nanoparticles', 'nanometals', 'particle size', 'NPs Au, 'NPs Ag', 'synthesis', and 'nanostructures' were found. In Cluster 2, terms such as 'animal experimentation', 'human cells', and 'in vivo studies' were found. Cluster 3 is based on 'drug release', 'procedures', 'diseases', 'liposomes', 'nanotechnology', 'nanomedicine', and 'targeted treatments', and Cluster 4 relates to 'cytotoxicity', 'cells', 'cell culture', and 'metabolism aspects'.

Table 5 shows the top-25 keywords based on occurrence. In this top-25 are words such as 'human', 'chemistry', 'nonhuman', 'controlled studies', 'gold and silver nanoparticles', and 'drug release', among the most important. In this study, words with more than 50 occurrences were determined, with 'nanoparticle', 'nanoparticles', and 'humans' having 670, 445, and 342 occurrences, respectively.

Table 5 Top-25 keywords according to occurrence degree.

Orden	Keyword	Cluster	Occurrences	Total link strength
1	Nanoparticles	3	670	4592
2	Nanoparticle	3	445	4280
3	Human	3	342	4120
4	Metal nanoparticles	1	341	2916
5	Article	2	317	3713
6	Chemistry	1	300	3583
7	Nonhuman	2	289	3682
8	Humans	3	274	3483
9	Animals	2	226	3104
10	Controlled study	2	216	2884
11	Animal	2	212	2952
12	Particle size	1	206	2289
13	Metal nanoparticles	1	187	2270
14	Gold nanoparticles	1	176	1451
15	Gold	1	163	1825
16	Gold nanoparticle	1	151	1784
17	Drug delivery system	3	149	1881
18	Priority journal	2	149	1904
19	Metabolism	4	140	1837
20	Review	3	140	1461
21	Procedures	3	133	1620
22	Synthesis (chemical)	1	125	686
23	Unclassified drug	2	125	1544
24	Nanotechnology	3	118	1096
25	Mouse	2	108	1683

Most Cited Key Articles

The most cited articles are listed in Table 6. These articles could represent the trends generated in the topic of metallic and non-metallic nanoparticles for the nanotechnology line. One of the application areas is the energy line, where Clavero in [25] investigated the development of more efficient systems in electron separation for solar energy conversion in photovoltaic and photocatalytic devices, in general, plasmonic energy conversion.

The concern of mankind in this accelerated growth of materials at the nanometer level brings some concerns, especially in health, so Manke *et al*. in [26] and Reidy *et al.* in [27], show topics of impact especially related to the incidence of NPs, including silver nanoparticles, in biological changes generating serious toxicity problems. One of these problems is oxidative stress and the ability to generate reactive oxygen species that interact with proteins, enzymes, and DNA and alter their functioning. Some other highly cited topics are related to solutions for biological tissue [28], treatments for diseases such as H1N1 [29], therapies in the development of tumors and cancer diseases [30,31], and system control through image processing [32].

Table 6 Analysis of the ten most cited articles in the period 2013-2022.

Year	Authors	Title	Journal	Cites
2014	Clavero C.	Plasmon-induced hot-electron generation at nanoparticle/metal-oxide interfaces for photovoltaic and photocatalytic devices	Nature Photonics	1896
2013	Manke A., Wang L., Rojanasakul Y.	Mechanisms of nanoparticle-induced oxidative stress and toxicity	BioMed Research International	922
2013	Reidy B., Haase A., Luch A., Dawson K., Lynch I.	Mechanisms of silver nanoparticle release, transformation, and toxicity: A critical review of current knowledge and recommendations for future studies and applications	Materials	735
2015	Duan H., Wang D., Li Y.	Green chemistry for nanoparticle synthesis	Chemical Society Reviews	618
2014	Rose S., Prevoteau A., Elziere, P. *et al.*	Nanoparticle solutions as adhesives for gels and biological tissues	Nature	534
2013	Kanekiyo M., Wei C.-J., Yassine H.M. *et al.*	Self-assembling influenza nanoparticle vaccines elicit broadly neutralizing H1N1 antibodies	Nature	491
2014	Zhang C.-L., Yu S.-H.	Nanoparticles meet electrospinning: Recent advances and future prospects	Chemical Society Reviews	456
2017	Riley R.S., Day E.S.	Gold nanoparticle-mediated photothermal therapy: applications and opportunities for multimodal cancer treatment	Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology	450
2018	Lin H., Chen Y., Shi J.	Nanoparticle-triggered: In situ catalytic chemical reactions for tumour-specific therapy	Chemical Society Reviews	423
2015	Shin T.-H., Choi Y., Kim S., Cheon J.	Recent advances in magnetic nanoparticle-based multi-modal imaging	Chemical Society Reviews	414

Conclusion

The scientometric analysis allowed finding trends related to metallic, bimetallic, and oxide nanoparticles in their applications in different areas of industry; however, the fields of greatest application were related to health, agriculture, energy, and the environment. There is an upward growth of scientific publications with an average annual growth rate of 13.5% in articles and 10.0% in patents; but the growth of patents annually exceeds more than ten times the production of articles.

The topics of greatest citation were centered on three main lines, the first related to the impact of nanoparticles on health and the environment due to their degree of toxicity; the second field is research applied to the treatment of tumors and cancer; and a third line is the use of imaging techniques for the treatment of materials.

The development of patents and scientific articles publications showed an upward trend, with the United States and China being the countries with the highest production; however, worldwide, more than three million applications will be filed in the year 2019 and 2020.

Acknowledgement

This work was supported jointly by the authors' research groups at the Universidad del Atlántico and Universidad Autónoma del Caribe institutions.

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Manuscript Received: 20 November 2022.
Revised Manuscript Received: 27 March 2023
Accepted Manuscript: 5 May 2023