

Global research output of nanobiotechnology research: a scientometrics study

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An effective scientometric analysis based on SCOPUS database was conducted to evaluate nanobiotechnology research from a different perspective for the period 2003–2012. Nanobiotechnology has been intensively investigated by bibliometric methods due to its technological importance and expected impacts on economic activity. The present study analyses nanobiotechnology research output during 2003–2012 on different parameters, including the growth, global publications share and citation impact, share of international collaborative papers and contributions of major collaborative partner countries. A total of 114,684 papers were published during 10 years, which received 2,503,795 citations with an average of 21.83 citations per paper. It has been observed that during 2003–2012, USA held the first position by number of publications (34,736), h-index (349), g-index (541), hg-index (434.52) and p-index (326.47). Developing countries such as India, China, South Korea and Canada showed increasing trends in their publications and their activity index also showed increasing trends. Top 10 institutions contributed 7.16% share of total publications. Massachusetts Institute of Technology, USA received the highest h-index (120) among the top 10 institutions. Biomaterials (1631) was the top journal of publication output; Nano Letters had the highest impact with an average citation per paper (73.86) and American Chemical Society received the highest h-index (158) among the top 10 journals.

Keywords: Bibliometric study, global research output, nanobiotechnology, p-index, scientometrics.

BIONANOTECHNOLOGY and nanobiotechnology are terms that refer to the intersection of nanotechnology and biology. Nanobiotechnology is essential in several industries, including pharmaceutical, chemical, and oil and gas, whereas bionanotechnology is a specific application of nanotechnology. Nanotechnology is an interdisciplinary field. Nanoscience and nanotechnology are considered as one of the promising research fields having important social and economic impacts in the future. There is a vast amount of published information in this field of research^{1–5}. Nanobiotechnology is relatively new to medical, consumer and corporate bodies. It is the union of engineering and molecular biology. The true promise of nanotechnology lies in the ability to manipulate materials on the same unbelievably small scale used by nature⁶. Two of the most promising technologies of the future are biotechnology and nanotechnology. Biotechnology: Use of living in the creation of wealth. Nanotechnology: Creation, investigation and utilization of systems that are 1000 times smaller than the components currently used in the field of microelectronics. The interface of these two worlds lies in nanobiotechnology. Nanotechnology deals

with developing materials, devices or other structures possessing at least one dimension sized from 1 to 100 nm. Biotechnology deals with metabolic and other physiological processes of biological subjects, including microorganisms. Association of these two technologies, i.e. nanobiotechnology can play a vital role in developing and implementing many useful tools in the study of life⁷.

Patent study⁸ of nanotechnology suggests that ‘the field is misconstrued as either a field of technology or an area of converging technologies while evidence to date suggests rather that nanoscience and nanotechnology be considered a set of inter-related and overlapping but not necessarily merging technologies’. Bionanotechnology, nanobiotechnology and nanobiology are terms that refer to the intersection of nanotechnology and biology⁹. Nanobiotechnology gives us the ever-growing scope for biotechnologist to explore better options of research in biotechnology. Derivatives of this subject of study are widely popular in several applications such as pharmaceutical, food, agriculture, consumer goods, etc. Institutes like the Life Science Foundation of India have recently introduced a diploma course in nanobiotechnology – advertised in *Current Science*¹⁰. In India, the field holds immense importance particularly in the nanomedicine sector. The arrival of nanobiotechnology in India has

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raised a series of questions and challenges in terms of intellectual property protection¹¹.

The present study is based on scientometric analysis of nanobiotechnology research output for the years 2003–2012. Scientometrics has typically been defined as the quantitative study of science and technology. Scientometrics includes all quantitative aspects of the science of science, communication in science and science policy¹². Mapping scientific fields is quite a common operation in bibliometric studies, in order to visualize networks explicitly or implicitly carried by articles (collaboration, citation). Different elements of a bibliographic record may be used to generate a map structure. Each element reveals a specific structure, unique in a sense, but always related to the structures based on other elements¹³.

The present study aims to capture the overall publications at macro level of the field among the top 10 countries and at the micro level relates to analysis of the subject nanobiotechnology. Hirsch¹⁴ introduced a single index to quantify a scientist's published research impact which created an unprecedented response from the scientometrics community. As an improvement of the *h*-index, Egghe¹⁵ proposed the *g*-index. Alonso *et al.*¹⁶ presented a new index called *hg*-index in order to reduce the disadvantages of using *h*-index and *g*-index, without affecting the advantages of both the measures. Non-parametric statistics enables us to honour both productivity and quality, whereas the impact may be lower in the case of averaging for the sole reason of higher productivity. These statistics share this appreciation of both productivity and citation rates with the *h*-index, but they differ from the *h*-index in that a range of tests for the significance of the impact (above or below expectation) becomes available. Less-cited papers can thus be appreciated proportionally, while the *h*-index uses the *h*-value as a threshold for the cut-off of the tails of the distributions^{17–19}. The metrics vary according to the particular methods used. In this study the various measures of collaboration and the indices like *h*-index, *g*-index, *hg*-index and *p*-index have been used to find the productivity and impact of the published work of a scientist or scholar of the priority countries.

Related literature

Meyer *et al.*²⁰ showed the interdisciplinary nature of nanotechnology and also looked at differences among countries during the period 1991–1996. Braun *et al.*²¹ focused on the scientific aspects of nanotechnology and described the rapid development of the field since the early 1990s. Chau *et al.*²² constructed a web portal about nanotechnology. Huang *et al.*^{23–26} monitored the research status of nanotechnology based on descriptive statistics and a citation network of countries, institutions and technology fields. Other studies also investigated nanotechnology

using bibliometric methods^{27–33}. In nanobiotechnology, nanotechnology provides the tools and technology platforms for the investigation and transformation of biological systems, and biology offers inspirational models and bio-assembled components to nanotechnology. Braun *et al.*³⁴ analysed 16 nano-titled journals dedicated entirely to the field to study the characteristics of the journals gatekeepers. Hajar and Nahid³⁵ looked into the scholarly activity of female researchers in the field of nanoscience and technology and compared it to that of male researchers. Schummer³⁶ analysed the development of scientists and engineers in nanoscale research of 600 published papers in eight existing nanoscale journals in 2002 and 2003, and also investigated multi- and interdisciplinary research collaboration in current nanoscale research. Worldwide nanotechnology research has experienced rapid growth in recent years. The status of nanotechnology research and development was studied in previous papers^{37–41}. Li *et al.*⁴⁰ conducted a longitudinal study of the worldwide nanotechnology development status using papers published in the Thomson *Science Citation Index (SCI) Expanded* database. Huang *et al.*²⁴ found that the major contributions of nanotechnology innovations are from the United States, Europe and Japan.

Bassecouard *et al.*⁴² used the methodology of citation analysis to obtain a database of all the nanotechnology publications from 1999 to 2003. They subsequently used cluster analysis to classify the literature into different disciplines (themes) according to the similarity of the papers in the references, that is, the source of knowledge or information. Igami and Okazaki⁴³ through a citation analysis mapped the nanotechnology field and classified the nanotechnology publications into 30 subfields.

Objectives

The objective of the current analysis is to identify 10 years research trend in nanobiotechnology with the aim to: (i) study global research trends related to nanobiotechnology, (ii) identify contribution and citation impact of most productive countries related to nanobiotechnology; (iii) catalogue the international collaboration among top 10 countries, (iv) identify the active performance of the countries using various indices, (v) identify the contribution of top 10 institutions and top 10 journals, (vi) study the authorship pattern, degree of collaboration, highly productive authors in the field of study, and (vii) identify and study the contribution of the most productive journals, institutions, etc. on nanobiotechnology.

Methodology

For the purpose of the study, the Scopus database was searched for all records of papers published in peer-reviewed journals and other bibliographical forms. Data

was collected from 2003 to 2012. This study is based on the world publication data on nanobiotechnology retrieved from the Scopus citation database [<http://www.scopus.com/search/>] for the 10 years (2003–2012). Defining a research domain via a set of queries is not a simple task⁴⁴. In this article, the main string used to retrieve data on nanobiotechnology was as follows:

(TITLE-ABS-KEY(nano*) AND TITLE-ABS-KEY(bio*)) AND PUBYEAR > 2002 AND PUBYEAR < 2013.

This may be too simple an approach⁴⁵, using ‘nano*’ as the query to define nanotechnology and considering it to be a useful approach when the domain is interdisciplinary and difficult to define; often experts in the field are themselves unable to agree on the precise nature of nanotechnology.

The indicators provided in this study are: (1) Benchmarking research performance of countries, institutions and scientists. (2) Trends in nanobiotechnology research publications. (3) Bibliographic form and language distribution of nanobiotechnology publications. (4) Single country publications, international collaborative publications, most collaborative country. (5) Average citation per paper. (6) Activity index, *h*-index, *g*-index, *hg*-index and *p*-index. (7) Most productive institutions and journals. (8) Authorship pattern, degree of collaboration. (9) Productivity and citation impact of world’s top 10 authors. (10) Highly cited papers (more than 2000 citations).

Results and discussion

Benchmarking research performance of countries

The global publication share of the top 10 most productive countries in nanobiotechnology research varied from 2.97 to 30.29% during 2003–2012. The United States topped the list with a share of 30.29%. China and Germany ranked second and third (with 16.58% and 7.02% share) followed by Japan and Germany at fourth to fifth position with publications share of 6.75% and 6.36% respectively. India, France, Italy and Canada ranked at seventh to tenth positions (their global publications share ranging from 2.97% to 4.62%).

The countries showing increase in their publications share from 2003 to 2012 included China (20.64%), followed by India (6.95%), South Korea (5.29%), Italy (3.94%) and Canada (2.95%). In contrast, the developed countries showing decrease in their publications share during the same period were USA (25.45%), Germany (6.02%), Japan (4.72%), UK (5.01%) and France (4.29%). All developing countries showed a rise in their publications share in nanobiotechnology research: China by 15.03%, followed by India (5.39%), South Korea

(2.51%), Canada (0.23%) and Italy (0.07%) from 2003 to 2012.

India ranked at seventh position among the top 10 most productive countries in nanobiotechnology research with its global publications share of 4.62% during 2003–2012. China and Canada ranked second and tenth with global publications share of 16.58% and 2.97% respectively during the same period. India’s global publications share increased from 1.56% to 6.95% from 2003 to 2012.

The quality of papers published by these 10 most productive countries in terms of citations per paper (Table 1) varied from 6.36 to 23.27 during 2003–2012. The highest citation impact was registered by Canada with 23.27 citations per paper, followed by South Korea (18.60), USA (18.42), Germany (17.65), China (15.94), Italy (15.81), UK (11.99), India (11.52) and France (8.42). Canada received more than world’s average citation per paper (21.83) and held the first position based on the citations received.

Trends in nanobiotechnology research publications

The world’s cumulative publication output in nanobiotechnology research consisted of 114,684 papers during 2003–2012, with an average number of 1146.84 papers per year. The world’s cumulative publications output increased from 2,944 papers in 2003 to 21,118 papers in 2012, witnessing a growth of 21.78%. Average percentage of growth of the study period was 1.76. The percentage of growth was more than the average percentage of growth in the year 2008 seems high (2.84%); whereas the percentage of growth for the year 2011 and 2010 was 2.20% and 2.13% respectively.

Bibliographic form and language distribution of nanobiotechnology publication, 2003–2012

From this study, 15 types of bibliographic form were found in a total of 114,684 publications during the 10-year study period. Articles (78,601) were the dominant document type, comprising 68.54% of the total production. Ninety-seven per cent of all articles were published in English. Thirty-two other languages also appeared, the most frequent being Chinese (2.06%), Japanese (0.40%), French (0.22%) and German (0.18%).

International productivity and collaboration

Data on international productivity and collaboration based on the affiliation information of authors were generated. Table 2 lists the top 10 productive countries with the number of single country publications and internationally collaborated publications. USA was the largest contributor,

Table 1. Publications output, share and rank of top 10 countries in nanobiotechnology research, 2003–2012

Country	Number of papers			Share of papers			TC	ACPP
	2003	2012	2003–2012	2003	2012	2003–2012	2003–2012	2003–2012
USA	1,120	5,374	34,736	38.04	25.45	30.29	1,099,375	18.42
China	165	4,358	19,015	5.60	20.64	16.58	333,259	15.94
Germany	308	1,272	8,050	10.46	6.02	7.02	224,555	17.65
Japan	196	997	6,562	6.66	4.72	5.72	128,145	6.36
UK	179	1,059	6,077	6.08	5.01	5.30	171,729	11.99
South Korea	82	1,118	5,362	2.79	5.29	4.68	102,830	18.60
India	46	1,468	5,295	1.56	6.95	4.62	84,095	11.52
France	165	907	5,235	5.60	4.29	4.56	104,820	8.42
Italy	114	832	4,359	3.87	3.94	3.80	79,601	15.81
Canada	80	623	3,406	2.72	2.95	2.97	87,126	23.27
World output	2,944	21,118	114,684	100	100	100	2,503,795	21.83

TC, Total citations; ACPP, Average citation per paper.

Table 2. Top 10 productive countries in nanobiotechnology research, 2003–2012

Top 10 countries	TP	TP%	Single country publications		International collaborative publications		MCC
			Number	Percentage	Number	Percentage	
USA	34,736	30.29	22,393	64.47	12,343	35.53	China (1831)
China	19,015	16.58	14,188	74.61	4,827	25.39	USA (1831)
Germany	8,050	7.02	2,075	25.78	5,975	74.22	USA (1137)
Japan	6,562	5.72	4,065	61.95	2,497	38.05	USA (571)
UK	6,077	5.30	1,430	23.53	4,647	76.47	USA (830)
South Korea	5,362	4.68	3,364	62.74	1,998	37.26	USA (951)
India	5,295	4.62	3,855	72.80	1,440	27.2	USA (415)
France	5,235	4.56	1,254	23.95	3,981	76.05	USA (556)
Italy	4,359	3.80	1,570	36.02	2,789	63.98	USA (570)
Canada	3,406	2.97	1,311	38.49	2,095	61.51	USA (645)

TP, Total publications; MCC, Most collaborative country.

publishing 34,736 articles on nanobiotechnology and China ranked second with 19,015 articles, followed by Germany (8050), Japan (6562), UK (6077), South Korea (5362), India (5295), France (5235), Italy (4359) and Canada (3406). The number of single country publications and internationally collaborated publications by these countries also ranked as the top 10 among all countries in nanobiotechnology research – 55,505 (48.39%) of the 114,684 articles were single country publications and 42,592 (37.14%) were internationally collaborated publications. Although single country publications dominated in nanobiotechnology research, international collaboration of researchers became more prevalent, which has also been a general trend in other fields⁴⁶. The proportions of internationally collaborated publications to the total output of these 10 countries showed significant disparity. Approximately 76% of the articles produced by UK and France involved other countries, whereas the proportion of collaborated articles in India only accounted for 27.2% (Table 2).

The international collaborative share of different countries in their national outputs in nanobiotechnology research varied from 25.39% to 76.47%, with highest publication share (76.47%) coming from UK followed by

France (76.05%), Germany (74.22%), Italy (63.98%) and Canada (61.51%) with more than 50% of their publications with international collaboration. Japan (38.05%), South Korea (37.26%), USA (35.53%), India (27.20%) and China (25.39%) produced less number of international collaborated publications.

One hundred and fifty countries were involved in the total research output ($n = 114,684$) on nanobiotechnology during 2003–2012. About 85% of total publications was contributed by the top 10 most productive countries, which indicates that the researchers from these countries were involved more in this field compared to other countries and 96% of total citations was received by the publications contributed by these top 10 countries. The total 19,709 (17.19%) papers are important as these are creating the major international impact. The papers may have significant theoretical and/or experimental novelty that is helping draw the attention of the research community (Figure 1).

Impact of contribution by countries

Different measures and indices have been developed for bibliometric studies. Taking a fixed number or a certain

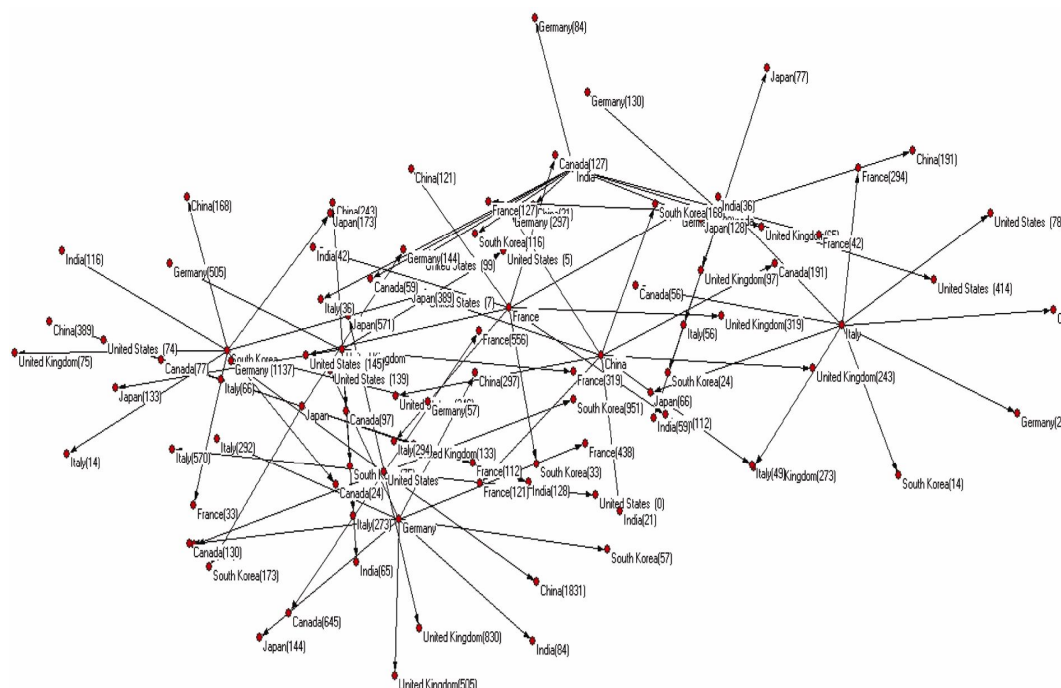


Figure 1. International collaboration among top 10 countries. (Note: Visualization using Pajek.)

percentage of all publications into consideration would mean a somewhat arbitrary and biased choice. To solve this problem, Hirsh¹⁴ introduced the *h*-index. The *h*-index is not an average, not a percentile, not a fraction; it is totally a new way of measuring performance impact, visibility, quality, etc. of the career of a scientist. It is a simple measure without any threshold. Based on the *h*-index various indices are developed for evaluating the career of individual scientists according to their scientific output. The *g*-index is an *h*-type index for quantifying the scientific productivity of scientists based on their publication record. The *h*-index and *g*-index describe the most productive core of the output of a researcher and inform about the number of papers in the core. Moreover, on-line databases such as *Web of Science*, *Scopus*, *Google Scholar* provide the *h*-index. Alonso *et al.*¹⁶ presented a new index called the *hg*-index. The *hg*-index of a researcher is computed as the geometric mean of his *h*- and *g*-indices, that is: $hg = \sqrt{h * g}$. Prathap⁴⁷ proposed an index called the *p*-index. This gives the best balance between quality (*C/P*) and quantity (*C*).

$$p = h_m = \left(\frac{C^2}{P} \right)^{1/3}$$

While ranking the countries by various indices, there is no variation in the case of USA. It holds first rank among the top 10 countries in various evaluations, followed by Germany in the second position, Japan in the fifth position and Italy in ninth position in all types of indices evaluation. China holds third position in both *h*- and *p*-indices and goes to the fourth position based on *g*- and

hg-indices. India holds eighth position in *h*-, *g*- and *hg*-indices and tenth position in *p*-index. This reveals that the *h*-index is only based on the citations and ranking of the citations received; the *g*- and *hg*-indices are based on the *h*-index only. But the *p*-index is based on both citations and publications and shows the best balance between quality and quantity (Table 3).

Activity index

Activity index (AI), as suggested by Frame⁴⁸, is based on the absolute publication output. Thus it is influenced by the size of the country and size of the field. AI characterizes the relative research effort a country devotes to a given subfield.

It is the ratio of the country's share of the world's publications output in the given field to the country's share of the world's publications output in all science fields, expressed as percentage. An AI > 100 reflects higher than average effort and AI < 100 indicates a lower than average effort by a country.

$$AI = (N_{ij}/N_{io}) / (N_{oj}/N_{oo}) \times 100,$$

where N_{ij} is the total number of publications of a country in a subject field *j*, N_{io} is the total number of publications of the country *i* in all the subfields, N_{oj} is the total number of publications for all the countries in the subfield *j* and N_{oo} is the total publications output for all subfields for all countries. AI for the top 10 countries for two blocks has been calculated and is shown in Table 4.

Table 3. *h, g, hg* and *p* indices of nanobiotechnology output of major countries

Country	TP	TC	ACPP	<i>h</i>	<i>g</i>	<i>hg</i>	<i>p</i>	Rank			
								<i>h</i>	<i>g</i>	<i>hg</i>	<i>p</i>
USA	34,736	1,099,375	18.42	349	541	434.52	326.47	1	1	1	1
China	19,015	333,259	15.94	169	242	202.23	180.09	3	4	4	3
Germany	8,050	224,555	17.65	180	282	225.30	184.34	2	2	2	2
Japan	6,562	128,145	6.36	127	221	167.53	135.77	5	5	5	5
UK	6,077	171,729	11.99	164	266	208.86	169.30	4	3	3	4
South Korea	5,362	102,830	18.60	127	193	156.56	125.40	5	6	6	8
India	5,295	84,095	11.52	114	176	141.65	110.13	8	8	8	10
France	5,235	104,820	8.42	66	145	97.83	128.03	10	10	10	7
Italy	4,359	79,601	15.81	104	172	133.75	113.28	9	9	9	9
Canada	3,406	87,126	23.27	115	188	147.04	130.62	7	7	7	6

Table 4. Activity index of top 10 countries

Country	2003–07		2008–12		Total
	TP	AI	TP	AI	
USA	11,064	117.30	23,672	93.24	34,736
China	3,433	66.49	15,582	112.10	19,015
Germany	2,563	117.25	5,487	92.23	8,050
Japan	2,270	127.40	4,292	88.08	6,562
UK	1,788	108.35	4,289	95.19	6,077
South Korea	1,154	79.26	4,208	106.16	5,362
India	708	49.24	4,587	117.82	5,295
France	1,519	106.86	3,716	95.49	5,235
Italy	1,132	95.64	3,227	99.44	4,359
Canada	952	102.93	2,454	96.00	3,406
Others	4,558	101.20	12,029	105.74	16,587
Total	31,141		83,543		114,684

AI, Activity index.

For countries having AI value more than 100 reflects their higher activity of nanobiotechnology research than the world average, as noticed in USA, Germany, Japan, UK, France and Canada during the first block period. During the second block period China, South Korea and India show higher activity of research. Hence there is an increase in the number of countries gaining higher AI from one block period to another block period. It is also observed that for any country, AI fluctuates from one block period to another block period. For developing countries like India, China and South Korea, AI in the first block was below 100 (49.24, 66.49 and 79.26 respectively) and increased in the second block period (117.82, 112.10 and 106.16 respectively) and shows their increasing trend in nanobiotechnology research publications.

Benchmarking research performance of institutions

The top 10 most productive institutions involved in nanobiotechnology research each published more than 700 papers during the study period 2003–2012. The publications profile of these 10 institutions along with their research output citation received and *h*-index values are presented in Table 5. These 10 institutions involved in

nanobiotechnology research together have contributed 7.16% share (with 8210 papers) in the cumulative world publications output in nanobiotechnology research, with an average of 821 papers per institution. Only four institutions have registered higher publications share than the group average. These are Massachusetts Institute of Technology (MIT; 1132 papers), National University of Singapore (1070), Chinese Academy of Sciences (838) and Seoul National University (832). The average citations per paper registered by the total papers of these 10 institutions were 27,754 during 2003–12. Only two institutions registered higher impact than the group average. The average *h*-index value of these 10 most productive institutions was 78.4 during 2003–2012. The four institutions scored higher *h*-index value than the group average of 78.4. Of these two institutions, the highest *h*-index value of 120 was achieved by MIT (Table 5).

Most productive journals

The 10 most productive journals publishing research papers in nanobiotechnology together contributed 12,794 papers, which accounts for 13.52% share of the world's total output during 2003–2012. Journals which published at least >950 papers related to nanobiotechnology research

Table 5. Productivity and citation impact of top 10 major world institutions in nanobiotechnology research

Top 10 institutions	TP	TC	<i>h</i> -index	Country
Massachusetts Institute of Technology	1,132	60,232	120	USA
National University of Singapore	1,070	42,099	104	Singapore
Chinese Academy of Sciences	838	21,573	70	China
Seoul National University	832	20,591	70	Seoul
Shanghai Jiaotong University	746	12,263	52	China
Nanyang Technological University	739	16,076	60	Singapore
Northwestern University	727	44,536	100	USA
Zhejiang University	722	14,361	56	China
Nanjing University	703	19,384	70	China
University of Michigan Ann Arbor	701	26,432	82	USA

Table 6. Most productive journals in nanobiotechnology research, 2003–2012

Top 10 journals	TP	TC	ACPP	<i>h</i> -index
<i>Biomaterials</i>	1,631	91,804	56.29	137
<i>Langmuir</i>	1,588	46,969	29.58	90
<i>Biosensors and Bioelectronics</i>	1,555	46,103	29.65	87
<i>Journal of the American Chemical Society</i>	1,394	100,055	71.78	158
<i>Journal of Nanoscience and Nanotechnology</i>	1,221	14,659	12.01	54
<i>Analytical Chemistry</i>	1,217	54,878	45.09	110
<i>Nanotechnology</i>	1,165	22,483	19.30	60
<i>ACS Nano</i>	1,035	36,933	35.68	87
<i>Journal of Materials Chemistry</i>	1,035	26,693	25.79	73
<i>Nano Letters</i>	953	70,390	73.86	128

during 2003–2012 are listed in Table 6. The total number of journal articles published by the world is 94,596.

Biomaterials (1,631) was the top journal by publication output, followed by *Langmuir* (1,588), and *Biosensors and Bioelectronics* (1,555). *Nano Letters* had the highest impact with ACPP of 73.86 and *Journal of the American Chemical Society* received the highest *h*-index of 158 among the top 10 journals. *Langmuir* ranked second in terms of total papers and it received the fifth rank in *h*-index. These core journals are in the subject areas of physics, materials science and engineering.

Authorship pattern

The analysis revealed that 8.56% of the publications are contributed by single authors and two-author contributions account for 13.01%. The study shows that more and more publications are being contributed under joint authorship. Alternatively, it can be said that there is an increasing trend towards multiple authorship. It can be inferred from the analysis that the nanobiotechnology authors are in favour of team research.

Degree of collaboration

The degree of collaboration (DC) in a discipline is calculated using the formula given by Subramanian⁴⁹

$$DC = N_m / N_m + N_s,$$

where N_m is the number of multi-authored research papers in a discipline published during a period, and N_s is

the number of single-author research papers in a discipline published during the same period.

Table 7 shows the cumulative and countrywise authorship pattern. Analysis on author collaboration was done by Subramanian's formula to find the degree of collaboration. The degree of collaboration of the top 10 countries lies between 0.91 and 0.99. During the period of study, the share of multi-authored papers was around 90%. This shows that the collaborative research is more predominant in the field of nanobiotechnology. Collaborative research is more effective than the single-author research and the production of the single-author research is less than 10% (Table 7).

Benchmarking research performance

Ten authors had 100 or more publications; Webster has published maximum number of papers, but Mirkin received maximum citations (14,822; Table 8). Ramakrishna had the highest *h*-index of 55. The *h*-index is insensitive to uncited papers and highly cited papers¹⁵. The publications profile of these 10 authors along with their research output, citations received and *h*-index values are presented in Table 8. These 10 authors together contributed 1,436 papers with an average of 143 papers per author and accounted for 1.25% share in cumulative world publications output during 2003–2012. Four authors published higher number of papers than the group average (143 papers). These are: Webster with 250 papers, followed by Yuan (180 papers), Chay (173) and Ramakrishna (151). Considering the quality/impact of

Table 7. Countrywise authorship pattern

Country	Single author	Two authors	Three authors	More than three authors	Total	Degree of collaboration
USA	2,549	5,392	5,915	20,880	34,736	0.93
China	224	1,354	2,518	14,919	19,015	0.99
Germany	111	568	737	6,634	8,050	0.99
Japan	403	651	983	4,525	6,562	0.94
UK	519	771	877	3,910	6,077	0.91
South Korea	118	484	843	3,917	5,362	0.98
India	219	1,056	1,159	2,861	5,295	0.96
France	294	303	465	4,173	5,235	0.94
Italy	195	290	423	3,451	4,359	0.96
Canada	148	537	644	2,077	3,406	0.96
Others	5,042	3,514	3,807	4,224	16,587	0.70
Total	9,822	14,920	18,371	71,571	114,684	0.91

Table 8. Productivity and citation impact of world's top 10 authors in nanobiotechnology research

Top 10 authors	Affiliation	TP	TC	<i>h</i> -index	Country
Webster, T. J.	Northeastern University, Department of Chemical Engineering, Boston, United States	250	5,687	40	USA
Yuan, R.	Southwest China Normal University, College of Chemistry and Chemical Engineering, Chongqing, China	180	3,870	32	China
Chay, Y.	Southwest China Normal University, College of Chemistry and Chemical Engineering, Chongqing, China	173	3,733	32	China
Ramakrishna, S.	National University of Singapore, Center for Nanofibers and Nanotechnology, Singapore City, Singapore	151	10,965	55	Singapore
Tan, W.	Hunan University, College of Chemistry and Chemical Engineering, Changsha, China	131	7,983	44	China
Wilner, I.	Hebrew University of Jerusalem, Institute of Chemistry, Jerusalem, Israel	120	10,885	51	Israel
Ju, H.	Nanjing University, Department of Chemistry, Nanjing, China	117	4,434	39	China
Weissleder, R.	Harvard Medical School, Department of Systems Biology, Boston, United States	109	7,417	44	USA
Mirkin, C. A.	Northwestern University, Department of Chemistry and International Institute for Nanotechnology, Evanston, United States	105	14,822	51	USA
Couvreur, P.	Universite Paris-Sud XI, Orsay, France	100	3,511	33	France

papers, these productive authors received a total of 73,307 citations for 1,436 papers. Five authors registered higher impact than the average impact of papers of all authors (7,330). Measuring the performance of these authors on the basis of *h*-index, five achieved higher *h*-index value than the group average of 42. These authors are Ramakrishna with *h*-index of 55, followed by Wilner (51), Mirkin (51), Tan (44) and Weissleder (44; Table 8).

Highly cited papers

Table 9 shows that most of the articles with multiple authors are highly cited. Out of the 11 articles, only 1 article was published by the country collaboration. Authors receiving more than 2000 citations are from

France, Japan, USA, UK and Australia. Among the highly cited papers, it was only one publication was international collaborated type by the author affiliation, i.e. UK, Australia. All the 11 publications were collaboration type by the author affiliations of each paper by single country publication with author affiliations from the same country and inter-institutionally collaborative publications with different author affiliations within the same country.

Conclusions

Due to technological importance and expected economic activity, nanobiotechnology has been intensively studied using scientometric methods. In this study we

GENERAL ARTICLES

Table 9. Highly cited papers (more than 2000 citations)

Author(s)	Title	Year	No. of citations received	Country of the author(s)
Daniel, M. C., Astruc, D.	Gold nanoparticles: assembly, supramolecular chemistry, Quantum-size-related properties and applications toward biology, catalysis and nanotechnology	2004	5,695	France
Kitagawa, S., Kitaura, R., Noro, S. I.	Functional porous coordination polymers	2004	4,966	Japan
Michalet, X., Pinaud, F. F., Bentolila, L. A., Tsay, J. M., Doose, S., Li, J. J., Sundaresan, G., Wu, A. M., Gambhir, S. S., Weiss, S.	Quantum dots for live cells, <i>in vivo</i> imaging, and diagnostics	2005	3,645	USA
Love, J. C., Estroff, L. A., Kriebel, J. K., Nuzzo, R. G., Whitesides, G. M.	Self-assembled monolayers of thiolates on metals as a form of nanotechnology	2005	3,381	USA
Sinha Ray, S., Okamoto, M.	Polymer/layered silicate nanocomposites: a review from preparation to processing	2003	3,286	Japan
Oberdorster, G., Oberdorster, E., Oberdorster, J.	Nanotoxicology: an emerging discipline evolving from studies of ultrafine particles	2005	2,633	USA
Nel, A., Xia, T., Madler, L., Li, N.	Toxic potential of materials at the nanolevel	2006	2,599	USA
Rosi, N. L., Mirkin, C. A.	Nanostructures in biodiagnostics	2005	2,394	USA
Gao, X., Cui, Y., Levenson, R. M., Chung, L. W. K., Nie, S.	<i>In vivo</i> cancer targeting and imaging with semiconductor quantum dots	2004	2,340	USA
Pankhurst, Q. A., Connolly, J., Jones, S. K., Dobson, J.	Applications of magnetic nanoparticles in biomedicine	2003	2,333	UK, Australia
Gupta, A. K., Gupta, M.	Synthesis and surface engineering of iron oxide nanoparticles for biomedical applications	2005	2,216	UK

have presented a summary of scientometric research in nanobiotechnology. Using publications from the literature, an overview of bibliometric efforts has been given to trace the emergence of this new technological area. The data show which countries are most active in terms of scientific publications in nanobiotechnology. To engage with nanobiotechnology successfully, developing countries would need to address a range of issues pertaining to research, technology development, skills requirement, institutions involved, risks issues, regulatory and governance structure and stakeholder engagement. Regulatory oversight for nanobiotechnology is necessary to channelize research efforts in a responsible direction. The regulatory regime for nanobiotechnology needs to be dynamic and should be reviewed from time to time. Transparency and public involvement in the design and implementation of regulatory structure in nanobiotechnology should be ensured. Market analyses and further studies remind us that there is still a long way ahead for this emerging area to become a generic discipline or technology.

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