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A bibliometric analysis on nanotechnology research

Mohammad Nazim[a] and Moin Ahmad[b]

[a]Assistant Librarian, Central Library, Banaras Hindu University, Varanasi-221005, E-mail: nazim@sify.com
[b]Assistant Librarian, Central Library, Integral University, Lucknow- 226026

Examines the scientific output in the field of 'nanotechnology', the aim being to offer an overview of research trends in this field and characterize its most important aspects such as growth of literature, authorship pattern, most productive journals, authors, countries, etc. A total of 2675 articles for the period of 1991-2006 were collected from Web of Science (WoS), especially via the Science Citation Index. The various analyses focus on the presentation of publications, frequencies and percentages. Authorship pattern and core journals were examined using Lotka's Law and Bradford's Law of scattering respectively. The yearly analysis shows that there is a rapid growth of nanotechnology research from the beginning of 21st century. When applying Bradford's law of scattering with respect to the identification of core journals, three concentric zones were defined with the ratio of 32:149:639, which are partially in accordance with the Bradford's distribution. With respect to the author productivity through the application of Lotka's law it was observed that the values obtained were widely different from the real values.

Introduction

Nanotechnology is the engineering of functional systems at the molecular scale. This covers both current work and concepts that are more advanced. In its original sense, 'nanotechnology' refers to the projected ability to construct items from the bottom up, using techniques and tools being developed today to make complete, high performance products[1]. K. Eric Drexler[2] popularized the word 'nanotechnology' in the 1980's and talked about building machines on the scale of molecules, a few nanometers wide—motors, robot arms, and even whole computers, far smaller than a cell. Drexler spent the next ten years describing and analyzing these incredible devices, and responding to accusations of science fiction. Meanwhile, mundane technology was developing the ability to build simple structures on a molecular scale. As nanotechnology became an accepted concept, the meaning of the word shifted to encompass the simpler kinds of nanometer-scale technology. The U.S. National Nanotechnology Initiative[3] was created to fund this kind of nanotech: their definition includes anything smaller than 100 nanometers with novel properties.

Information managers have adopted quantitative methods in recent years in order to evaluate library resources and services more objectively and effectively. Bibliometrics is one of the quantitative techniques of citations analysis to measure the records of human communication through the process of collection, counting, analysis and interpretation of citations given in various types of literature and thereby helping in identification of significant sources of information. Present study was taken up to quantify and map the world's strength of scientific output in the field of 'nanotechnology', the aim being to offer an overview of the growth of nanotechnology research world over and to characterize its most important aspects such as growth of literature, authors' collaboration, most productive countries and researchers, etc.

Objectives

This study explores the growth of scientific output in the field of nanotechnology over time using bibliometric analysis, the aim being to offer an overview of research trends in this field and identify its most important aspects. The main objectives of the study address the following aspects:

1. Chronological evolution of number of articles,
2. Identification of core journals in the field of nanotechnology and the application of Bradford's law as an indicator of the dispersion of scientific literature,
3. Authorship pattern (number of authors contributing each article) and most productive authors with their temporal evolution,

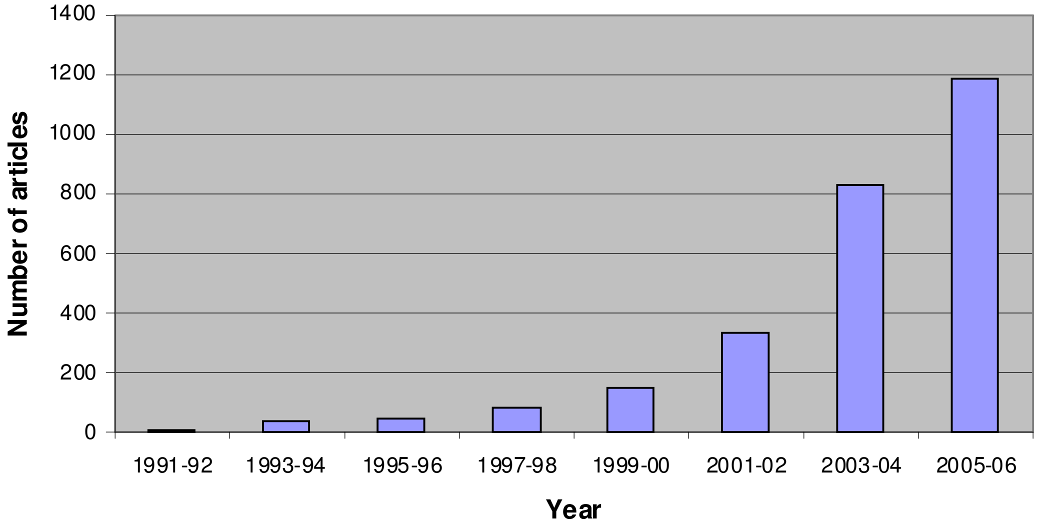

Fig. 1 — Growth of literature

4. Author productivity through the application of Lotka's law,
5. Output of various languages,
6. Output with respect to country and its evolution, and
7. Analysis of the subject areas showing the greatest interest in nanotechnology.

Methodology

The articles included in the present study were collected from the Web of Science (WoS) database of the Institute for Scientific Information (ISI), Thomson Scientific, Philadelphia (USA), via the Science Citation Index (SCI-EXPANDED). WoS is a multidisciplinary bibliographic database that provides information from approximately 8700 international journals and is used to map world wide science and technology data[4]. With the aim of covering all the available citations on the subject, the above mentioned database was searched using the following term: 'nanotechnology' and 'nano technology'. Citations for the period 1991-2006 were downloaded using EndNote-7 Software provided by Thomson ISI web of knowledge. Since the database was searched via two terms, 9 records were found as duplicates and were removed using EndNote's duplicate removal application. Only journal articles were included in the study. Therefore, books, proceedings, book reviews, etc., were all excluded.

Having applied the above method, a total of 2675 records were collected and data were tabulated using SPSS v.14.0[5]. The coded variables were as follows: year of publication, number of authors contributing to the articles and country/institute to which they belong, the names of journal in which articles were published, the subject areas covered by these journals, and language of the article.

Results

The analysis in the present study focused mainly on the frequencies and percentages of publications. In addition, however, the productivity of journals and authors was described using Bradford's Law of scattering and Lotka's Law respectively.

Growth of literature

A total of 2675 articles were published during 1991-2006, thus on an average, 167 articles were published each year. This reveals an upward trend in the number of articles published. In 1990s there were few studies on nanotechnology, whereas the beginning of the 21st century saw a proliferation of such publications compared with the previous years. Figure 1 show how there is an increasing number of publications over time.

Output of journals

The journals publishing maximum number of articles in any subject area are considered as core journals. The 2675 articles analyzed in the present study were published in 820 journals from various scientific fields. Of these 32 journals were identified as core journals which published about one third of the total articles (Table 1), whereas remaining two third were scattered among 788 journals. After applying Bradford's Law of scattering with respect to the identification of core

Table 1—Core journals

S. no.	Name of journal	Number of articles	%	Impact Factor
1	*Angewandte Chemie-International edition*	89	3.32	10.232
2	*Nanotechnology*	81	3.02	3.037
3	*IEEE Transactions on Nanotechnology*	78	2.91	1.909
4	*Nano Letters*	42	1.57	9.960
5	*Microelectronic Engineering*	39	1.45	1.398
6	*Journal of Nanoscience & Nanotechnology*	34	1.27	2.194
7	*Chemistry A-European Journal*	32	1.19	5.015
8	*Journal of Nanoparticle Research*	31	1.15	2.156
9	*Langmuir*	31	1.15	3.902
10	*Applied Physics Letters*	30	1.12	3.977
11	*Proceedings of National Academy of Sciences of USA*	29	1.08	9.643
12	*Nature*	23	0.85	26.681
13	*Journal of Applied Polymer Sciences*	22	0.82	1.306
14	*Material Science & Engineering C-Biomimetic Supramolecule Systems*	22	0.82	1.325
15	*Applied Surface Science*	21	0.78	1.436
16	*IEEE Transitions on Magnetics*	20	0.74	0.938
17	*Journal of American Chemical Society*	20	0.74	7.696
18	*Chemphyschem*	19	0.71	3.449
19	*IEEE Translations on Electron Devices*	19	0.71	2.052
20	*Small*	19	0.71	6.024
23	*Japanese Journal of Applied Physics*	18	0.67	1.222
24	*Journal of Physical Chemistry B*	17	0.63	4.115
25	*Diamond & Related Materials*	16	0.59	1.935
26	*Advanced Materials*	15	0.56	7.896
27	*Journal of Polymer Science P-A Polymer Chemistry*	15	0.56	3.405
28	*Journal of Polymer Science P-B Polymer Physics*	15	0.56	1.622
29	*Journal of Vacuum Science & Technology B*	15	0.56	1.597
30	*Nucl. Instrum. Methods Phys. Res. Sect. B-Beam Interact. Mater. Atoms*	15	0.56	0.946
31	*Biomaterials*	14	0.52	5.196
32	*Macromolecular Symposia*	14	0.52	——-

Table 2—Bradford's distributions of articles over different journals

Zone	Number of journals (observed)	Number of articles (observed)	Number of journals (expected)	Number of articles (expected)
First	32	883	32	892
Second	149	898	160	892
Third	639	894	800	891
Total	820	2675	992	2675

journals, three concentric zones were defined. The core or zone 1 contained 883 (33% of the total) articles that were published in thirty two journals. The second zone contain 898 articles (33.58%) published in a total of 149 journals, the number of their respective publications ranging from 4 to 13 articles. Finally, zone 3 consisted of 639 journals publishing one to three articles, accounting for a total of 894 (33.42%) articles. The most productive journals in the subject nanotechnology are shown in more detail in Table 1.

Bradford' distribution

As an indicator of the dispersion of scientific output, Bradford[6, 7] proposed a model of concentric productivity

Table 3—Contribution for each articles by number of authors

Number of authors	Number of articles	%
1	460	17.20
2	589	22.01
3	431	16.11
4	391	14.62
5	266	9.94
6	189	7.06
7	118	4.41
8	88	3.28
9	49	1.83
10	31	1.16
11	22	0.82
12	11	0.41
13	11	0.41
14	6	0.22
16	6	0.22
19	1	0.03
20	1	0.03
21	2	0.07

Table 4—Author productivity

Number of articles	Number of authors	%
1	6664	84.21
2	891	11.25
3	205	2.59
4	79	0.99
5	33	0.41
6	22	0.27
7	9	0.11
8	2	0.025
9	2	0.025
10	6	0.075
12	2	0.025
25	1	0.012

zones with a decreasing information density. Thus, according to this law, each zone or core contains a similar number of articles, but the number of journals in which these are published increases from one zone to the next according to the expression I, n, n2,…; in this way, a group of journals dedicated more specifically to the subject of interest can be distinguished. Thus the ratio between three zones should be in the ratio of 32:160:800, while the ratio in each zone of the present study is 32:149:639, which are partially in accordance with the Bradford's distribution. The zone wise distribution of articles in different journals is shown in Table 2.

Number of authors

The number of authors contributing to each article ranged from one to twenty one. However, 17.20% articles have single author while 38.13% have two or three authors. Articles with more than three authors account for 46.67% of the total number of documents which clearly indicates that collaborative efforts are more common in the field of nanotechnology research. Contribution for each article by number of authors is shown in detail in Table 3.

Author productivity

During 1991-2006, a total of 7917 authors contributed 2675 articles with an average of 2.95 authors per article. Table 4 shows the distribution of the number of articles published by each one of the authors, and reveals that whereas one author (Seeman, N.C.) contributed as many as 25 articles, others only contributed a few.

As can be seen, 84.21% of authors contributed to only one article each, those contributing to more than one therefore being much fewer in number. About 11.25%

Table 5—Author productivity based on Lotka's Law

Number of articles (x)	Number of authors (Observed) (y)	Number of authors with n=2	Number of authors n=2.9
1	6664	6664	6664
2	891	1666	892
3	205	770	275
4	79	416	119
5	33	266	62
6	22	185	36
7	09	136	23

Table 6—Number of publications and temporal evolution of the most productive authors

Author	Country	1991-1992	1993-1994	1995-1996	1997-1998	1999-2000	2001-2002	2003-20	2005-2006	Total
Seeman, N.C.	USA		2		1	4	3	8	7	25
Roco, M.C.	USA						5	3	4	12
Sleytr, U.B.	Austria		1	1	4	1	1	2	2	12
Sastry, M.	India						2	6	2	10
Ferrari, M.	USA				1	1	2	3	3	10
Mao, C.D.	USA				1	2		3	4	10
Pum, D.	Austria		1	1	2	1	1	2	2	10
Cingolani, R.	Italy						2	5	3	10
Webster, T.J.	USA							2	8	10
Chen, Y.	USA							3	6	9
Khomutov, G.B.	Russia							7	2	9
Kim, J.	USA							5	3	8
Lee, S.C.	USA				1		2	4	1	8
Guo, P.X.	USA							4	3	7
Kawazoe, Y.	Japan						1	5	1	7
Li, J	USA					1	1	3	2	7
Merkle, R.C.	USA		1		2	2		1	1	7
Meyyappan, M.	USA						1	2	4	7
Montelius, L.	Sweden							3	4	7
Namatsu, H.	Japan					2		3	2	7
Nicilini, C.	Italy						1	4	2	7
Rinaldi, R.	Italy						2	4	1	7

and 2.59% authors have contributed two and three articles respectively. Only nine (0.12%) authors published ten or more studies.

To count the frequency of publication by the authors, Lotka's Law was applied. According to this law the number of scientists who contributed 'n' papers must be $1/n^2$ of those who contributed only one, therefore, the exponent of 'n' is often fixed at 2, in which case the law is known as the inverse square law of scientific productivity[8-10]. Considering the fact that 6664 authors have produced only one article each, the value of n can easily be derived.

To find out the value of n the study started with the premise of n=2. The values obtained widely different from the real values (Table 5). As the calculated values were much higher than the real values, the calculations were carried out with the increased values of n. In order to save time and shorten the procedure, the study determined the values of n that matches with the number of authors who have contributed two papers each using the formula.

$$x^n y = c \qquad \text{(eqn.1)}$$

Putting the value of x=1, and y=6664, the calculation obtained was;

$1^n .6664=C$

$6664= \;C$

Putting the value of x=2, and y=891, and C=6664, the calculation obtained was;

Table 7—Language-wise distribution of articles

S. no.	Language	Number of articles	%
1	English	2608	97.5
2	German	21	0.78
3	Chinese	13	0.49
4	Japanese	11	0.41
5	French	7	0.26
6	Croatian	4	0.15
7	Polish	3	0.11
8	Russian	3	0.11
9	Portuguese	2	0.07
10	Spanish	1	0.03
11	Finnish	1	0.03

Table 8—Most important subject areas

S. no.	Subject areas	Number of articles	%
1	Material science multidisciplinary	624	11.52
2	Physics applied	560	10.34
3	Nanoscience & nanotechnology	443	8.18
4	Chemistry multidisciplinary	435	8.03
5	Engineering electrical & electronic	343	6.34
6	Physics condensed matter	341	6.30
7	Chemistry physical	240	4.43
8	Multidisciplinary science	153	2.83
9	Engineering multidisciplinary	138	2.59
10	Polymer science	132	2.43
11	Instrument & instrumentation	96	1.77
12	Optics	85	1.57
13	Biotechnology & applied microbiology	81	1.50
14	Biochemistry & molecularbiology	80	1.48
15	Engineering chemical	67	1.24
16	Others	1595	29.46

Table 9—Most productive countries

Countries	Number of articles	%
USA	1085	40.56
Germany	267	9.98
Japan	250	9.34
England	167	6.24
Peoples R. China	154	5.76
Italy	98	3.66
France	96	3.59
Switzerland	78	2.92
India	67	2.50
Canada	65	2.43
Others	348	13.00

$2^n.891 = 6664$
$2^n = 6664/891$
$n\log 2 = \log 7.479$
$n\,(0.301) = 0.873$
$n = 0.873/0.301$
$n = 2.9$

Using the value of n=2.9, the number of authors contributed two, three or more articles each were computed in Table 5.

From the analysis it has been observed that, research trends have been changed and inverse square law of scientific productivity in the present study does not match exactly to the Lotka's law.

From the analysis, most productive authors has been identified in the field of nanotechnology. Table 6 lists 22 most productive authors of various countries with their individual contribution in different years.

Output with respect to language

An exhaustive analysis of the articles under study revealed that literature on nanotechnology published in various languages. Table 7 shows the languages in which most articles published on the subject nanotechnology. It can be seen that 97.5% articles were published in English language and remaining 2.5% articles were published in 10 other languages.

Subject areas

The analysis of the subject areas of the journals consulted was conducted according to the criteria of the Journal Citation Report (JCR) for SCI. It is observed that the literature on nanotechnology was scattered in the journals of 145 subject areas. It was also observed that same journal was included in more than one subject areas and therefore, number of articles calculated in the total subject areas is around double from those analyzed in the study. Taking into account that the same journal may be included in more than one subject area the results obtained are those shown in Table 8**.**

Among a total of 145 subject areas it can be seen that the greatest interest in the study of nanotechnology is shown in the area material science multidisciplinary, followed by physics applied and nanoscience and nanotechnology. These three, together with chemistry

Table 10 — Most productive countries and their temporal evolution

Year	USA	Germany	Japan	England	China	Italy	France	Switzerland	India	Canada
1991-1992	4	2		2						
1993-1994	11	5	4	6				4		1
1995-1996	15	9	3	3			2	6		
1997-1998	31	10	10	6	1	2	3	7		
1999-2000	56	21	11	14	1	3	7	9		3
2001-2002	137	38	38	23	18	12	12	10	9	5
2003-2004	330	72	85	46	39	36	36	18	22	19
2005-2006	501	110	99	67	95	45	36	24	36	37
Total	1085	267	250	167	154	98	96	78	67	65

multidisciplinary, engineering electrical and electronic and physics condensed matter, account for around 50% of the total subject areas represented by the articles reviewed.

Countries

In studying this variable, countries were ranked from greater to lesser productivity on the basis of affiliation of authors to the institutions of the countries, taking into account that authors from different countries may contribute to the same article. The list of countries is quite long as a total of 69 countries published 2675 articles. The country-wise distribution is shown below in Table 9.

The country with the greatest output in terms of research on nanotechnology is the USA (40.56%), followed by Germany and Japan, with a total of 267 (9.98%) and 250 (9.34%) articles respectively. Subsequent positions are occupied by England (6.24%), China (5.76%), Italy (3.66%), France (3.59%), Switzerland (2.92%), India (2.50%) and Canada (2.43%), the remaining countries publishing a total of 348 articles between them accounting for 13% of the total output.

In terms of temporal evolution of the number of publications for each of the most productive countries, it is noted that the research trend on nanotechnology started in the USA, Germany and England in the early 1990s, whereas Japan, Switzerland and France started in the mid of 1990s. Research on nanotechnology in Italy, Japan, China and India started quite late but secured positions among top ten countries. The temporal evolution of the number of publications for each of the most productive countries is shown in Table 10.

Conclusion

From the growth of literature on the subject one may visualize that the interest of research on nanotechnology grew considerably during last decade of the 20th century, particularly since 1995 and beginning of the 21st century saw a proliferation of such growth. Bradford's law of scattering with respect to the identification of core journals in the field was found successfully applicable as out of total literature published in 820 journals, one third was covered by only 32 journals which may be considered as core journals in the field of nanotechnology. With respect to the author productivity through the application of Lotka's law it was observed that the values obtained were widely different from the real values. Collaborative research was found common in the field of nanotechnology as 83% of the total articles were contributed by two or more than two authors. The areas showing the most interest in the subject of nanotechnology are those related to material science, applied physics, nanoscience & nanotechnology, chemistry, engineering, electrical & electronic and physics condensed matter. Although the authors contributing to the articles analyzed originated from 69 different countries, most output (around 87%) was distributed across only ten countries, the most productive being the USA. English was found the most popular language with 97.5% of the total articles.

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