Scientometrics (2011) 86:15–25
DOI 10.1007/s11192-010-0304-7

A collective and abridged lexical query for delineation of nanotechnology publications

Morteza Maghrebi · Ali Abbasi · Saeid Amiri · Reza Monsefi · Ahad Harati

Received: 29 March 2009 / Published online: 3 November 2010

Abstract In order to monitor articles/patents in nanotechnology, there is little agreement on a universal lexical query or even an explicit definition of nanotechnology. Here in the light of a proposed definition, a set of case studies has been conducted to remove keywords which are not exclusive to nanotechnology. This resulted in a collective and abridged lexical query (CALQ) for nanotechnology delineation. Through bibliometric quantification of already-proposed as well as the novel keywords, it was shown that all keywords included in CALQ have considerable exclusive retrieval and precision, while the removed keywords do not satisfy either of these numerical thresholds. This approach may also be applied for the future updating of CALQ.

Keywords Nanotechnology · Lexical query · Bibliometric study · Delineation

Introduction

There are frequent reports of an emerging field of science and technology which is commonly called *Nanotechnology* nowadays. Nanostructured materials/systems are believed to have numerous advantages over their counterparts (Hiramoto et al. 2006),

Electronic supplementary material The online version of this article (doi:10.1007/s11192-010-0304-7) contains supplementary material, which is available to authorized users.

M. Maghrebi (✉)
Chemical Engineering Department, Faculty of Engineering, Ferdowsi University of Mashhad,
P. O. Box 91775-1111, Mashhad, Islamic Republic of Iran
e-mail: mmaghrebi@um.ac.ir

A. Abbasi · S. Amiri
Iranian National Nanotechnology Initiative, P. O. Box: 14395-1336, Tehran, Islamic Republic of Iran

R. Monsefi · A. Harati
Computer Engineering Department, Faculty of Engineering, Ferdowsi University of Mashhad,
P. O. Box 91775-1111, Mashhad, Islamic Republic of Iran

revolutionizing many markets such as healthcare (He et al. 2008), automotive (Nanotechnology for automotive energy 2007) and energy (Mao and Chen 2007).

Accordingly, many investors and decision makers in the industry and government have paid attention to the nanotechnology (Roco 2005; Huang et al. 2004; Helland and Kastenholz 2008). However, in order to make policies, planning and decision-making effectively, one needs to monitor the prevailing trends by use of some measurable indicators.

Bibliometric delineation of published articles/patents is one of the essential tools for monitoring scientific/technological trends, and nanotechnology is not an exception. The bibliometric delineation is realized through a standard information retrieval approach which enables distinctions to be made between relevant and irrelevant articles/patents in a scientific/technological database (e.g. Science Citation Index), in order to retrieve and count them (Zitt and Bassecoulard 2006).

The cornerstone for any bibliometric quantification practice is to build up a lexical query (LQ). LQ can be defined as a set of keywords/terms organized with suitable Boolean operators (e.g., OR, AND, NOT), in order to retrieve the desired articles/patents totally and exclusively.

Definitely to introduce a LQ, one has to have a clear definition of the pertaining scientific area (here nanotechnology) in advance. However, nanotechnology is a multidisciplinary field and its borderlines with some other well-established scientific disciplines have not completely drawn yet (Morrow et al. 2007; Robinson et al. 2007; http://www.nanotec.org.uk/evidence/65aJasonWiggins.htm). In fact, because of little agreement on a general definition for nanotechnology, delineation (i.e., separating relevant articles/patents from irrelevant ones) is an undeveloped theme in the nanotechnology.

Accordingly, first by exploring the preceding definitions of nanotechnology, an explicit definition is suggested. Then through case study of articles retrieved by the previous LQs, a collective and abridged lexical query (CALQ) is proposed. It will be shown, that CALQ has both high precision and recall.

Definitions of nanotechnology

As abovementioned, a widely-accepted definition of nanotechnology is an ideal starting point for a bibliometric delineation study, but does such a standard definition exist in this area?

Although nanotechnology is widely referred to, there is insufficient agreement on what exactly nanotechnology is. Some different definitions have already been suggested for nanotechnology. These definitions have given more or less special attention to the nanoscale domain (e.g., sub-micrometer, or 1–100 nm domain/feature size). In some cases, the size issues have also been associated with the concept of *novel functionalities*.

Taniguchi who first defined nanotechnology in 1974, pointed to some criteria such as *size of one nanometer*, *extra high accuracy* and *ultra fine dimensions*. These criteria are obviously very wide and indistinct and embrace many matured topics which could not present such an emerging area. For instance, common polymers comprise of nanoscale strands with quite definite strand width, but nobody recognize these non-targeted randomly-oriented molecules as nanotechnology members.

The Finnish nanotechnology program had more specific explanation about the size scale. It defined nanotechnology as “an increasing number of methods which are used to build structures smaller than finest structures in current silicon chips, yet larger than individual atoms. This implies a scale from 1 nm to 1000 nm" (TEKES and Academy of Finland).

Franks (1987) added functionality to his definition. He defined nanotechnology as "the technology where dimensions or tolerances in the range 0.1–100 nm (from the size of an atom to the wavelength of light) play a critical role".

The European Commission has paid special attention to the delineation of nanotechnology in the project, *Mapping Excellence in nanotechnology*. According to this definition, nanotechnology is "the manipulation, precision placement, measurement, modeling or manufacture of sub-100 nm scale matter" (Mayer et al. 2001; Noyons et al. 2003).

In United States, Nanoscale Science, Engineering and Technology (NSET) Subcommittee of National Science and Technology Council's Committee on Technology has introduced the following definition: "Research and technology development at the atomic, molecular or macromolecular levels, in the length scale of approximately 1–100 nm range, to provide a fundamental understanding of phenomena and materials at the nanoscale and to create and use structures, devices and systems that have novel properties and functions because of their small and/or intermediate size" (http://www.nsf.gov/crssprgm/nano/reports/omb_nifty50.jsp).

The recent definition is almost the most-developed one and applicable to the most of well-known topics in the nanotechnology researches; so many institutions use this definition to set their boundaries for nanotechnology. Nonetheless, even this definition is not completely clear (Bawa 2007). Some parts of this definition, such as *novel properties*, are ambiguous and may make debate. For instance, there are some evidences about utilization of nanoparticles ($\sim$20 nm) to produce size-dependent optical effects in the medieval lusterwares (Borgia et al. 2004; Pradell et al. 2008).

So far, there is no global consensus about nanotechnology definition. Only the ISO committee on nanotechnology has just recognized the scale range of approximately 1–100 nm for the nanotechnology delineation (ISO/TS 27687:2008).

Nanotechnology lexical queries

Some efforts have made to present appropriate LQs for the nanotechnology bibliometric studies. Braun et al. (1997) were probably the first, who analyzed early growth of the nanotechnology articles during the period of 1986–1995. They provided a set of simple keywords which had mostly begun with *nano* prefixes. Similarly, a website belonging to Thomson Scientific (http://www.esi-topics.com/nano) employed statistical studies on the articles published in 1991–2000. In this study all the articles which contained nano-prefixed words in their abstracts, have been recognized as nanotechnology articles. In another similar study on US patents, Marinova and McAleer (2003) considered nano-prefixed words as nanotechnology identifiers; though patents related to *nanosecond* and the chemical compounds, $NaNO_x$, had been excluded. Obviously some well-known nanotechnology-specific keywords, such as fullerene, do not have *nano* prefixes. Therefore a large number of articles/patents could not be retrieved by the abovementioned LQs.

Noyons et al. (2003) offered an extensive LQ containing the instrumental and biological keywords. As we discuss later on, these keywords are not specific to nanotechnology and so result in low precision. Huang et al. (2004, 2005). also recognized/employed several keywords such as *nano**, *self assemble** and *quantum dot** for retrieving nanotechnology patents, but the used LQ suffered from the same unspecific keywords.

A more elaborate LQ has been employed by the Centre for Science and Technology Studies (CWTS), in order to prepare a database of high-tech articles/patents published by

European countries (Calero et al. 2006). In spite of large volume and complexity of this LQ, it neglects some major nanotechnology-specific keywords, such as dendrimer.

Recently, Warris (http://www.science.org.au/policy/nano-report.pdf) from the Australian Academy of Science (AAS) has improved CWTS' work a great deal. He presented his huge LQ in 9 categories which include almost all the above LQs. There are, however, some drawbacks concerning its precision and recall which will be discussed thoroughly later.

Methodology

A straightforward definition for the nanotechnology

In order to refine a LQ from non-specific keywords, first we need to rely on a clear definition of nanotechnology. Here, we suggest a brief and explicit definition, resulted from rearrangement of the NSET definition, as follows:

> Nanotechnology is the targeted and controlled synthesis/manipulation of materials, structures, devices and systems with accuracy/feature size of approximately 1–100 nm and preferably 2–50 nm.

Thanks to this unambiguous definition, the following familiar topics could be totally excluded from nanotechnology realm:

- Non-controlled, non-targeted and empiric synthesis of nanostructures (e.g., traditional synthesis of carbon black).
- Studies which are not in the scope of foregoing dimension, either greater or smaller (e.g., general submicron particles or simple chemical compounds).
- Employing natural (non-man-made) nanostructures without any nanoscale manipulations (e.g., covalent immobilization of proteins on the surfaces or extraction of diamondoids from the crude oil). Gopel et al. (1997) has discussed the differences of man-made and natural nanostructures in the course of nanotechnology delineation more thoroughly.
- Mere employing characterization tools conventional to nanotechnology or developed by it (e.g., applying AFM in order to map the surface of an ordinary bulk metal). This is a common debate in the delineation of nanotechnology studies (Huang et al. 2004).

A collective and abridged lexical query (CALQ)

In light of the chosen definition for nanotechnology, we conducted an extensive case study on all keywords found in the previous LQs, as well as some novel keywords. These case studies revealed the precision as well as retrieval amount of each keyword. By removing the low-retrieval and low-precision keywords, we reached the following collective, yet abridged lexical query (CALQ) for retrieving the nanotechnology articles (and potentially the nanotechnology patents):

> *(nano* not nano2 not nano3 not nanog not nanosecond* not nanomol* not nanogram* not nanoplankton*) or "atom* scale" or "atomic layer deposition*" or "giant magnetoresist*" or graphene* or dendrimer* or fulleren* or c-60 or "langmuir–blodgett*" or mesopor* or "molecul* assembl*" or "molecul* wire*" or "porous silicon*" or "quantum dot*" or "quantum well*" or "quantum*

comput" or "quantum wire*" or qubit* or "self assembl*" or supramolecul* or "ultrathin film*"*

In contrast to previous LQs, CALQ is definition-based and brief. Later on we will show that CALQ has also a balanced precision and recall.

Evaluation of keywords

In order to demonstrate the precision and recall of CALQ, we compared it with Warris' lexical query (WLQ) (http://www.science.org.au/policy/nano-report.pdf), as the most matured LQs developed so far for the nanotechnology delineation. In fact, WLQ was not just an example, but considered as a collection of all the previous keywords proposed for the nanotechnology delineation. Noteworthy, segmentation of WLQ to the individual keywords was based upon a simple rationale; in each category of WLQ, the phrase located between two successive *OR* operators was considered as an individual keyword.

Evaluations of the keywords were conducted in the Science Citation Index Expanded database (ISI Web of Science). The queries were limited to the *articles* and *all languages* options, and also to *Publication Year* of 2008 (There were also some queries for the year 2007, but the discussions are merely focused on the results of 2008). All data were retrieved during 1st to 4th November 2009.

At first, we put our focus on the retrieval quantity as an approximate measure of the recall. For each studied keyword, we defined *exclusive retrieval*. It refers to a set of articles which could be retrieved only by that keyword and not by any other keyword included in the CALQ. In fact, we can divide retrieval of each keyword into shared articles with other keywords of the CALQ as well as the unshared ones. The latter was regarded as the exclusive retrieval of each studied keyword and can be simply obtained using a *NOT* operator. The exclusive retrieval (ER_i) of keyword i (K_i) may be typically represented as:

$$ER_i = RR(K_i) - RR(K_i \cap CALQ),$$

where RR is retrieval result. In another word, ER_i could be considered as what is positive by K_i and negative by CALQ. The lower the ER_i, the higher coverage domain (and potentially total recall) of CALQ, and so the less importance of K_i to be included in the CALQ.

To make comparisons more meaningful, we introduced relative exclusive retrieval (RER_i). It was calculated for each specific keyword as below:

$$RER_i = (ER_i/ER_{base}) \times 100\%,$$

where ER_{base} is the exclusive retrieval of nano-prefixed words, as most common keywords in the nanotechnology (see Nano-prefixed keywords section and Table 4 presented in supporting online material).

Then one needs to figure out which keyword is and which keyword is not significant. In this study, keywords with RER_i less than 0.15% ($RE_i \leq 50$) were considered to be potentially insignificant.

After removing the low-RER keywords, a set of case studies was conducted on the articles retrieved exclusively by each of the remaining keywords of WLQ. In each case study, 20 highly-cited articles were chosen and carefully read in light of conceptual relevance with the proposed definition of nanotechnology. The false and true positive results were used in calculation of precision data. The keywords with precision equal or lower than 50% were considered to be irrelevant to nanotechnology—to demonstrate the conceptual irrelevancy of these keywords with the proposed definition of nanotechnology, a sample irrelevant article was presented for each omitted keywords. Obviously, the remaining keywords had RERs higher than 0.15% and precisions higher than 50%, and so are legible to be included in CALQ.

To enhance CALQ furthermore, we also introduced some novel nanotechnology keywords which had not been included in WLQ or previous LQs. Some of these keywords matched the both thresholds, and some just matched the precision threshold. The first group was already included in CALQ, and confirms CALQ correctness, while the latter could help in future updating of CALQ.

Finally, we calculated the precision and recall of CALQ upon successive addition of its keywords in a precision-descending manner. The precision and recall result of whole CALQ was then compared with that of WLQ (http://www.science.org.au/policy/nano-report.pdf) and Noyons et al. (2003). The calculation of recall data was based upon total of 1,120 articles retrieved in the precision evaluation stage.

Results and discussion

RER-based exclusion of keywords

As mentioned before, the main objective of this study is to introduce a simple LQ, which could retrieve high portion of nanotechnology publications. By removing low-RER keywords, listed below, only keywords with high potential recall are considered. Therefore, while the query will have high recall, it remains as short as possible.

> *"atom* manipulat*", "ballistic transport*", "biocompatible membrane*", "biocompatible surface modification*", "coulomb blockade*", "DNA comput*", "low dimensional structure*", "modified virus*", "molecul* channel*", "molecular catalys*", "molecular comput*", "molecular electronics", "molecular engineering", "molecular manipulation", "molecular membrane*", "organometallic catalysis", "PDMS stamp", "positional assembl*", "quantum array*", "quantum cellular automat*", "quantum device*", "quantum ratchet*", "quantum size effect*", "rational drug design", "resonant tunnel*", ("self organized growth" OR "self organised growth"), "single electron logic", "single electron transistor*", "single electron* tunnel*", ("site-specific" AND ("gene therapy" OR "drug delivery" OR "drug action" OR "gene delivery")), ("surface modification" AND ("molecular layer*" OR multilayer* OR "layer-by-layer")), "synthetic membrane*", "synthetic receptor*", ("thin film*" AND micropor*), "thin solid films", "ultraviolet lithograph*", (encapsulat* AND virus*), (NEMS or "nanoelectromechanical system*")*

Table 1 (presented in supporting online material) contains the corresponding RERs of the abovementioned keywords, which have fallen below the selected threshold. There were six keywords with RER near zero, and the highest value (0.145%) corresponds to a long keyword referring to *site-specific drug delivery*.

Precision-based refinement/exclusion of keywords

After removing the low-RER keywords of WLQ, the remaining ones were analyzed regarding their relevance to the nanotechnology. The case studies revealed that there were few high-precision keywords in the WLQ, but the remaining keywords could be classified into the following:

1. Nano-prefixed words, which should be refined.
2. Characterization-based keywords which are unspecific to nanotechnology, according to our explicit definition.
3. Life science and biotechnology keywords which are unspecific to nanotechnology, according to our explicit definition.
4. Keywords unspecific to nanoscale, according to majority of nanotechnology definitions.

Now we discuss these four categories separately in the following sections.

Nano-prefixed keywords

It is obvious that the majority of nanotechnology articles contain nano-prefixed words. Therefore, these articles have to be investigated first. WLQ retrieves these articles as *Nanoa* or nanob* or nanoc* or nanod*, etc*. We have used *nano** instead of this long phrase.

Predictably, there are a lot of low-precision nano-prefixed words. These irrelevant words could be classified into two major groups. The first group includes the numerous low-RER words. Because of high diversity of these words, it is not practical to exclude them one-by-one by the *NOT* operators. However, the second group includes frequent words, which retrieve a significant number of articles. WLQ excluded some of these unrelated words, and we extended them. As a compromise between precision and recall, we refined nano-prefixed keywords of CALQ as below:

(nano not nano2 not nano3 not nanog not nanosecond* not nanomol* not nanogram* not nanoplankton*)*

The precision of this phrase as a whole was 90% (see High-RER and high-precision keywords section and Table 4 presented in supporting online material). As mentioned earlier, RER of this keyword was considered 100%, as a basis for comparing other keywords.

These excluded keywords are quite common and also irrelevant to the nanotechnology. For instance, *nano3* (RER= 0.6%, precision $\sim$0) actually refers to $NaNO_3$ or sodium nitrate; a chemical compound located completely out of the nanotechnology.

Instrumentation keywords

The second category of WLQ includes instruments used in the nanotechnology characterization, such as *atomic force microscopy*. Almost all of these instruments were invented more than two decades ago. Nowadays, mere employment of these instruments does not guaranty an article to be a nanotechnology-related one. In fact, it should also comprise synthesis/manipulation of a nanoscale object (and so a nanoscale keyword). Hence characterization-based keywords could not satisfy the proposed definition of nanotechnology and may not be considered in the CALQ. The highest precision 35% belonged to *scanning force microscopy*, while this value for *scanning probe microscopy* was calculated to be zero (see Fig. 1). Table 2 in supporting online material includes the exemplified irrelevant articles, as well as their precision and RER results.

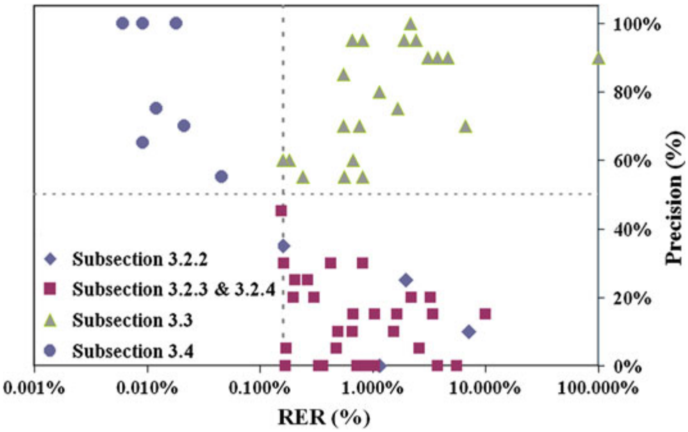

Fig. 1 The scatter plot of investigated keywords in the plane of precision and RER. Each category of points is named according to the corresponding subsection number. The detailed list of each category is available in supporting online material: Keywords listed in Table 2, Table 3, Table 4 and Table 5 correspond to subsection Instrumentation keywords, subsection Life science and biotechnology keywords & Keywords unspecific to nanoscale, subsection High-RER and high-precision keywords and subsection Low-RER and high-precision keywords respectively

Life science and biotechnology keywords

Categories 6, 7, 8, and 9 of WLQ were mostly related to biotechnology and life science which have had their well-established boundaries. Clearly, almost all the biomolecules have at least one nanometric dimension, but the nanoscale accuracy was not the key aspect in the majority of retrieved articles. While some of these keywords had significant RER as high as 10% (*one-dimensional structures*), their precisions were mostly lower than 20%. There were also eight keywords with precision around zero (see Fig. 1 and Table 3 in supporting online material). This justifies the exclusion of these keywords from CALQ.

Keywords unspecific to nanoscale

Some keywords in WLQ relate to feature sizes which are not in the nanoscale range (i.e., approximately 1–100 nm). So, they fail to be considered as nanotechnology keywords, according to the most of nanotechnology definitions, as well as our definition. In Fig. 1, some points correspond to such keywords. For instance, *MEMS* which stands for micro-electromechanical system is clearly in the scale of micrometer—a domain sensibly greater than nanoscale. The precision of *MEMS* was only 5%, while that of *electron beam lithography* was as high as 45%. See Table 3 in supporting online material.

High-RER and high-precision keywords

Undoubtedly, after removing the low-RER and low-precision keywords, the remaining ones should satisfy the numerical thresholds of RER as well as precision. Table 4 in supporting online material shows all these keywords, along with some novel keywords, which have not been considered in WLQ or any LQs in the past (Fig. 1). As could be seen in this table, these high-RER and high-precision keywords exactly coincide with those of

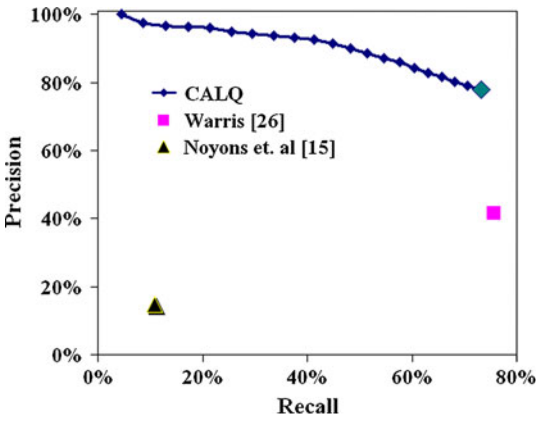

Fig. 2 The precision and recall data of CALQ upon successive addition of its keywords in a precision-descending manner (according to Table 4 reported in supporting online material), compared with those of Warris (http://www.science.org.au/policy/nano-report.pdf) and Noyons et al. (2003)

CALQ. This confirms that CALQ has reached its goal as a short and high-precision LQ. The highest precision (100%) was observed for *fullerene*, while the lowest precision (55%) was obtained for the case of *atomic scale* and *molecular wire*. Also, RER results ranged from 0.16% for the case of *quantum wire* to expectedly 100% regarding *nano-prefixed words* (Fig. 1).

To clearly demonstrate precision and recall performance of CALQ, its keywords were sorted in a precision-descending manner. Upon successive addition of these keywords, the precision and recall were calculated. As shown in Fig. 2, the precision and recall of complete CALQ are 78.3 and 73.6% respectively. This precision is quite higher than that of WLQ (http://www.science.org.au/policy/nano-report.pdf) (41.5%) and Noyons et al. (2003) (14.7%). However, the recall of CALQ is slightly lower than that of WLQ (http://www.science.org.au/policy/nano-report.pdf) (75.6%). This recall is acceptable for CALQ, accounting its quite shorter length.

Low-RER and high-precision keywords

Our extensive case studies also suggested some novel high-precision keywords, which failed to be included in CALQ, due to their low-RER. As could be seen in Fig. 1, there are 3 keywords with precision as high as 100%, but the RER values are not higher than 0.05%. These keywords are reported in Table 5 in supporting online material.

Noteworthy, these keywords may be considered in the periodic update of CALQ; since they may become high-RER in the future. Moreover, one may revise the aforementioned threshold for RER, in order to increase the recall of CALQ in cost of losing the precision.

Conclusion

After the comparison of different definitions and lexical queries of nanotechnology, a new collective and abridged lexical query (CALQ) was suggested. It is based on an explicit proposed definition of nanotechnology and two adjusted numerical thresholds. It is well-suited for the bibliometric studies, because of its unmatched simplicity and precision as well as its reasonable recall.

Noteworthy, the keywords of CALQ was selected on the basis of data retrieval in a specific time span. Thus, CALQ may be updated periodically, as nanotechnology bifurcates and shifts into new realms. It may also be revised, if a globally-accepted definition would be offered for nanotechnology, or a higher recall for CALQ would be required.

Acknowledgment We would like to thank Morteza Adine-nia as well as Davoud Gharailou for their useful helps and comments.

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