IDENTIFYING EMERGING NANOPARTICLE ROLES IN BIOSENSORS

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Abstract
This paper profiles R&D on the application of nanoparticles in biosensors and explores potential application development pathways. The analysis uses a dataset of nanotechnology publication records for the time period 2001 through 2008(part year) extracted from the Science Citation Index. It focuses on emergent research activities prominent in the most recent 3 years. Bibliometric analyses are employed to ascertain R&D trends and research networks for key biosensors, and extrapolating models are used to forecast the technological trend for nanoparticle-based biosensors. In addition, a combination of quantity (publication) and quality (citation) analysis for nanoparticle-based biosensors helps position the leading countries in this research field. Science overlay mapping helps us see the different emphases of nanoparticle-based biosensors research between the US and China. Most recent studies present that nanoparticles relating to biosensors show significant maturation. Biosensors, enabled by nanoparticles, show promise for improvement in stability, sensitivity, selectivity and indirect detection. This paper demonstrates how bibliometric analyses can help anticipate emerging technology development and application potential.

Keywords: Nanoparticles, Biosensors, Bibliometric analysis, Citation analysis, Trend analysis

Introduction

Nanotechnology is playing an increasingly important role in the development of sensors. Biosensors represent an especially exciting opportunity for high-impact applications benefiting from “nano” attributes. As to a biosensor, the vital parameters are its sensitivity and detection ranges. Many sensors operate through the variation of a surface parameter, like surface conductivity, with analyte concentration. Hence, the effective surface area of the device, i.e. the area actually interacting with the analyte, determines the sensitivity. For increasing the surface area, nanomaterials, especially nanoparticles, provide an easy answer. In recent years, a wide variety of nanoparticles with different properties have found broad application in biosensors. Owing to their small size (normally in the range of 1-100nm), nanoparticles exhibit unique chemical, physical, and electronic properties that are different

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from those of bulk materials (c.f., Luo, 2006), the high surface-to-volume ratio of nanoparticles has been exploited for improving the performance of biosensors.

Reviewing the studies of recent years, we can find that many kinds of nanparticles, including metal nanoparticles, oxide nanoparticles, semiconductor nanoparticles, and even composite nanoparticles, have been widely used in biosensors. Furthermore, different kinds of nanoparticles, and sometimes the same kind of nanoparticles, can play different roles in different biosensor systems. For instance, gold nanoparticles show potential to facilitate molecular bonding to detect glucose in the micromolar concentration range. Aided by silver nanoparticles, amperometric biosensors show improved biocompatibility useful in pesticide detection. Palladium nanoparticles have been tried to fabricate a sensitivity-enhanced electrochemical DNA biosensor. Functional nanoparticles (electronic, optical, and magnetic) bound to biological molecules (e.g. peptides, proteins, nucleic acids) have been developed for use in biosensors to detect and amplify various signals (c.f., Chen, 2004). Nowadays, nanoparticles relating to biosensors show significant maturation. Researchers tend to combine nanoparticles into the materials used for biosensors in order to improve the sensitivity of the system in potential sensing applications. Most recent studies show that biosensors composed with nanoparticles do take on rapid, simple, and accurate measurements, which offers exciting new opportunities for the development of biosensor capabilities.

Owing to the emerging roles that nanoparticles are playing in the improvement of biosensors in recent years, it is necessary and meaningful for us to investigate the researches of nanoparticle-based biosensors from the point of view of management of technology. As a vital part of management of technology, grasping the latest development of technology and identifying the emerging characters can help us get competitive advantages in the future (c.f., Porter, et al., 1991). Although nanoparticle-based biosensors have been researched and affirmed to provide remarkable functional improvements, few studies have tried to systematically present the functions and roles of nanoparticles in biosensors (c.f., Shipway, 2008). It is the aim of this paper to profile R&D on the application of nanoparticles in biosensors and explore potential application development pathways.

Approach and Data

In this paper, bibliometric analyses are employed to ascertain R&D trends and research networks for nanoparticle-based biosensors. Bibliometric analysis is a tool for extracting information from large databases looking for patterns and explained reasons for apparently unstructured behavior (c.f., Daim, 2005). In the field of technology management, bibliometric analysis can play important roles from three aspects. The first is technology forecasting. After getting historical data from authoritative databases, we can adjust these bibliometric data using an S-curve as a way to fit the technological growth process (c.f., Daim, 2006), analyzing research trends and identifying emerging areas of technology. Secondly, bibliometric methods can help determine the technology life cycle position and get its maturity level. Martino (c.f., Martino J. 2003) presents bibliometric analysis dividing the data in five categories. As he described, when the technological development is at the basic research stage, the Science Citation Index (SCI) nicely represents that literature. When the technological development reaches the applied research stage, the technological literature is well represented by the Engineering Index (EI) literature (for certain technologies). When development reaches the experimental development phase, patent documentation is a good reflection. When the development reaches the application stage, Newspaper Abstracts depict activity patterns. At last, bibliometrics can investigate information through the use of different indicators such as publications, cited references, occurrences of words, phrases, citations, co-citations, authorship and related characteristics that may extract hidden patterns from structured data, presenting the whole picture of research networks and relationships(c.f., Watts RJ, 2001).

The datasets used in these bibliometric studies come from global nanotechnology publications for the time period 2001 through 2008(part year) extracted from different databases: SCI, Inspec, Compendex, and Factiva. This paper focuses on SCI data for intensive study to capture the emergent research activities, especially those prominent in the most recent 3 years. The SCI dataset of publications here is developed using the definition of nanotechnology and the data-cleaning methods described by Porter et al. (2008). Our basic search terms include "nano*" and 7 modular term sets to capture nano-related articles; "biosensor"; and "nanoparticles." In addition, besides these basic search terms, we add other terms like specific categories terms of biosensor (such as glucose, electrochemical, amperometric, optical and enzyme) and variants of nanoparticles (such as Ag, Au, Pt, Cds, Pbs, MnO_2, SiO_2 and TiO_2). Using this approach, 1400 publication records were drawn from SCI to create a dataset for the 2001-2008(mid-year) time period. At the same time, we also set up two other datasets drawn from the Inspec & Compendex databases with 1715 records, and from Factiva with 489 records. However, the search method for these later datasets is much simpler than that used for the SCI dataset, just using basic search terms of "nano*", "biosensor," and "nanoparticles."

Results

We begin by showing a trend line based on the cumulative number of publications by each of the three datasets (Figure 1). We are trying to find out the development status of nanoparticle-based biosensors. Apparently the overall trend of the publication counts keeps increasing, which shows that nanoparticles have played a more and more important role in the research and application of biosensors in recent years. Examining these three growth curves, we find that 2004 is the key time point for both the SCI and Inspec & Compendex data series. At about that time, the basic research and the more applied research on nanoparticle-based biosensors accelerated into a steeper rate of growth. In comparison, the publication counts of Factiva, reflecting broader business and general public attention, started to increase more steeply in 2007. This suggests that the popular business application of nanoparticles in biosensors lags basic and applied research by about three years.

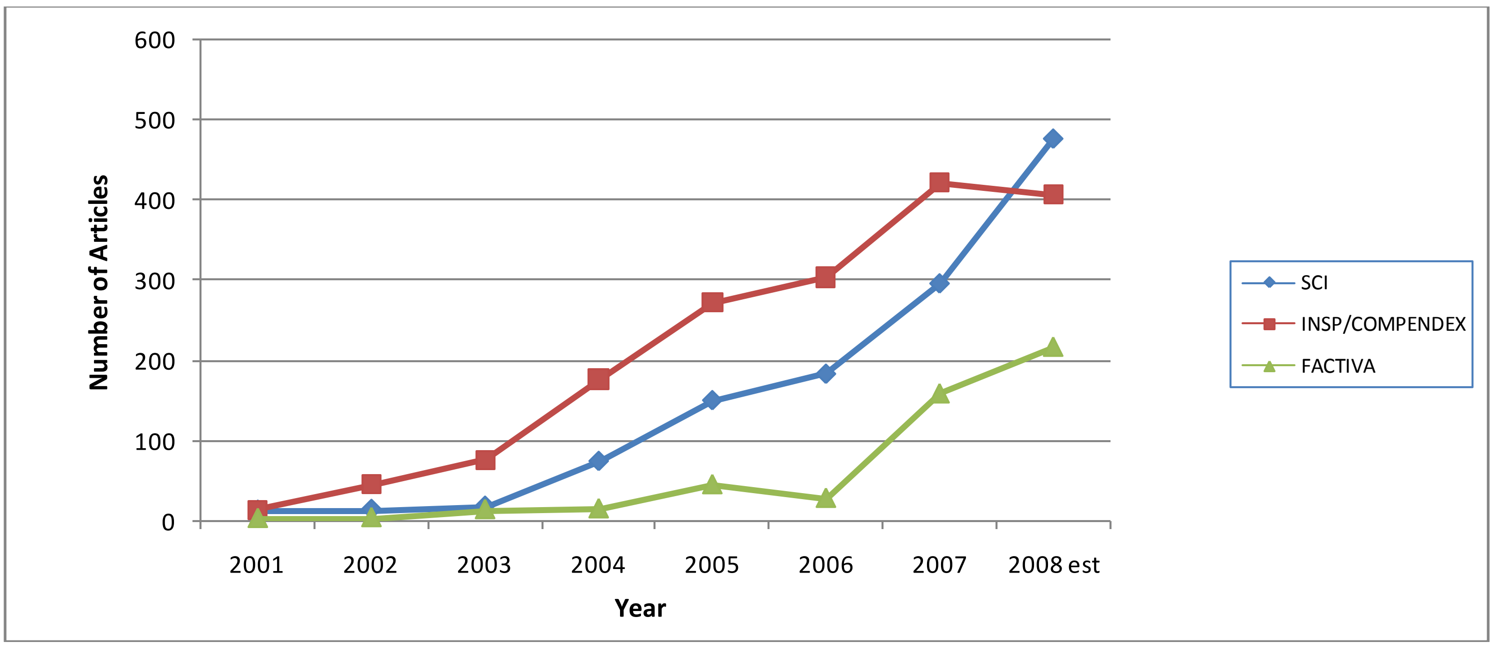

Fig. 1: Cumulative publications of nanoparticles applications in biosensor by Database[4]

What is likely to happen in the near future? The last data point for the INSP/Compendex series is estimated because our data reflect only about half of the expected complete 2008 tally. That said, we still note that this point indicates a possible slight decline in applied research on the topic. On the other hand, the increasing rate of publications for SCI in the most recent two years hints that a further expansion of applied R&D could be anticipated in about two years. So, those interested in tracking this emerging technology would want to monitor

[4] Databases used: Science Citation Index, INSPEC&COMPENDEX, and Factiva, 2001-2008(estimated). In order to get more accurate result for the comparison analysis for these three datasets, search terms for SCI in this chart are the same with the other two datasets with "nano*", "biosensor" and "nanoparticle".

developments quite closely in the coming couple years to ascertain the development pattern.

In order to gain a richer perspective on the technology life cycle position and maturity level for nanoparticle-based biosensors, we extrapolate the technological trends for them. Figure 2 gives one result of trend analyses of publications indexed by SCI through the year 2012. Bibliometric data can be adjusted using an S-curve as a way to fit the technological growth process. Here, we choose a Gompertz Model to fit the data with a high coefficient of 0.99. It precisely presents that a steep growth could continue over the next few years. Similarly, trend analyses were done for the data from the INSPEC & Compendex datasets with one result shown on Figure 3. Using a Gompertz Model with coefficient of 0.96, the data follows an increasing trend over the next 4 years. According to the results of our trend extrapolation, we can estimate that there is still a long time for the basic research and applied research of nanoparticle-based biosensors to grow.

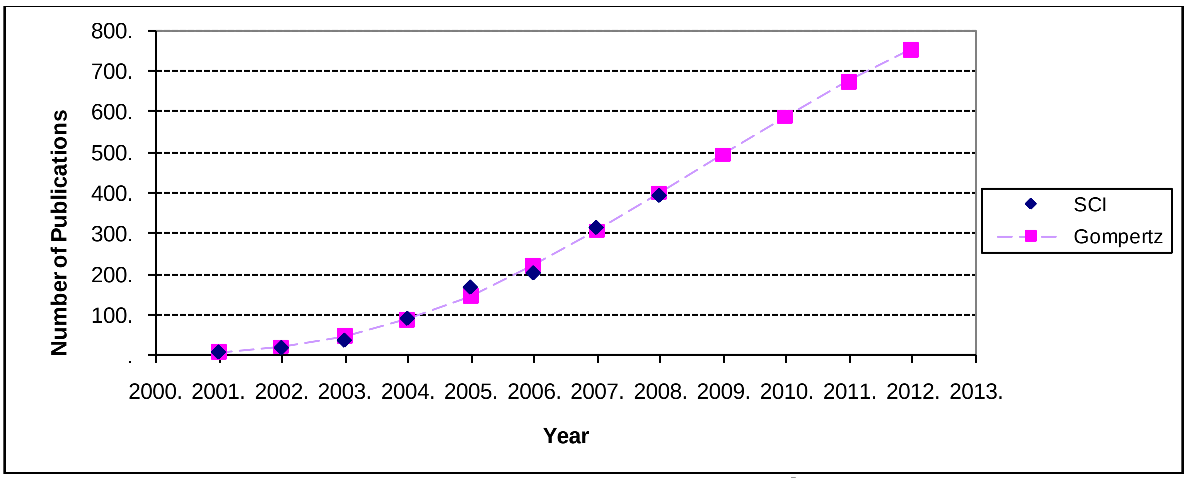

Fig.2: Gompertz Model fit to the Bibliometric data[5]

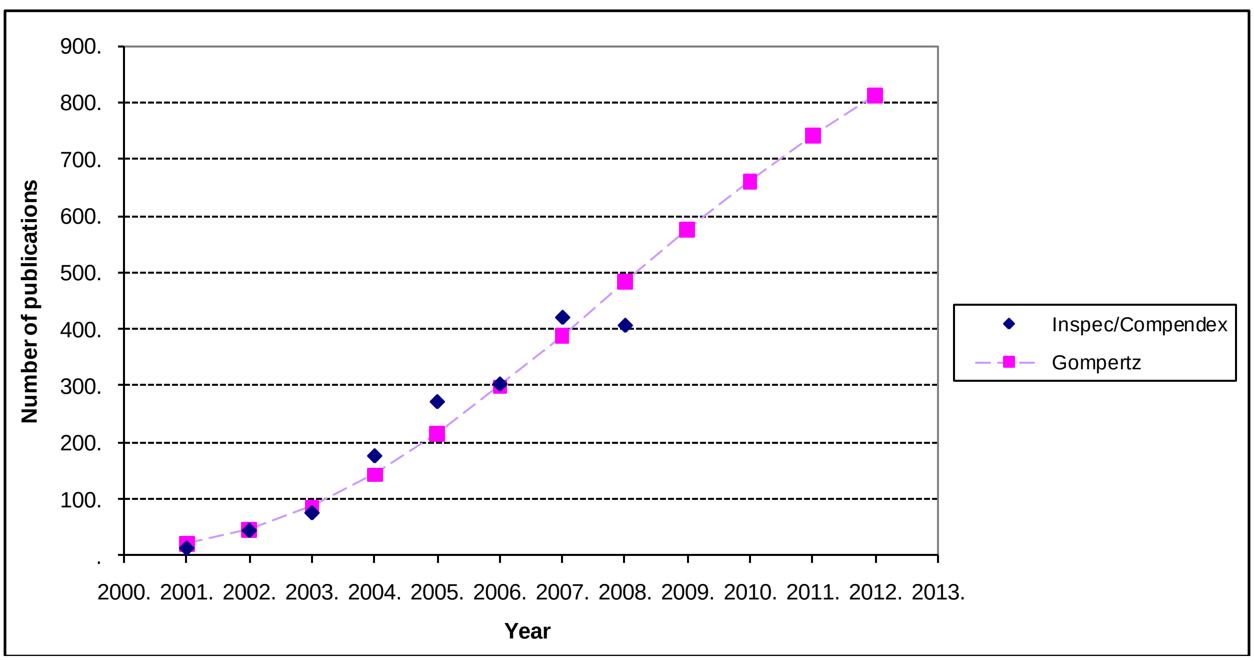

Fig.3: Gompertz Model fit to the Bibliometric data[6]

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[5] Database used: SCI. Search terms are "biosensor" and "nanoparticle."

*The limit of Gompertz Model here is equal to 1200, and Coeff Det. is equal to 0.99, which is higher than other models, such as Fisher-Pry Model and Exponential Model.

[6] Database used: INSPEC/COMPENDEX. Search terms are "biosensor" and "nanoparticle."

*The limit of Gompertz Model here is equal to 1200, and Coeff Det. is equal to 0.96, which is higher than other models, such as Fisher-Pry Model and Exponential Model.

The evidence is strong that nanotechnology has recently become one of the most exciting forefront elements in biosensor R&D. Given the observed high level of research activity, we want to consider potential application developments. In particular, we seek to distinguish the functional roles of nanoparticles in biosensors compared with the other nanomaterials.

In order to get the position of nanoparticle-based biosensors among all the nanomaterial-enhanced biosensors, this paper partitions the bibliometric data. We separate the publication counts of nanoparticle-based biosensors from the publications counts of any nanomaterial-enhanced biosensors. We then establish a ratio between these. The publications of nanoparticle-based biosensors are primarily from the results of searching the terms, "nanoparticle" and "biosensors." The publications of nanomaterial-enhanced biosensors come from the results of searching the term "nano*" with "biosensors." Based on these bibliometric data, we again seek to examine the trend and to forecast the technological growth process of nanoparticle-based biosensors using suitable growth models. In Figure 4, a Linear Model is used to fit the ratio data from SCI for 2001 to 2008 and gives another trend trajectory extended to the year of 2012. In Figure 5, a Linear Model is employed to fit the data from INSPEC/COMPENDEX. According to the results shown in these two charts, we can estimate that nanoparticle-based biosensors have more potential than other nanomaterial-based biosensors in the next few years because the value in the year 2012 is still smaller than the Limit of "1." However, to some extent we were concerned by the goodness of fit of the two trend analyses, because the coefficients of determination of these two models are not very high (0.78 and 0.79, respectively). Those coefficients just affirm the visual appearance – the fit of the line is not so strong in the earlier years; however, it is quite close in the more recent years.

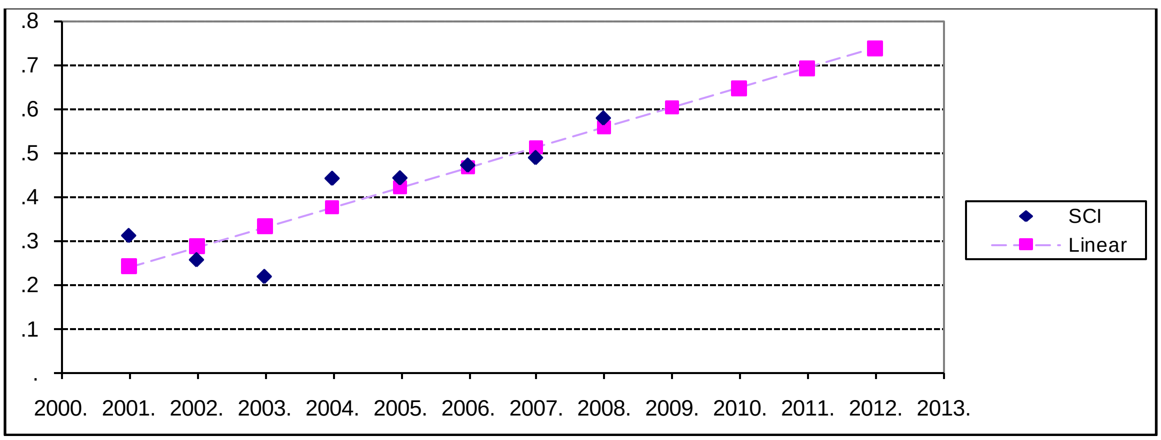

Fig.4: Linear Model adjust to the Bibliometric data[7]

[7] Database used: Science Citation Index. The limit of Linear Model here is 1.0, and Coeff Det. is 0.78.

The value of the points in the chart represents the ratio of publication counts of nanoparticle-based biosensors divided by publications counts of any nanomaterial-based biosensors. The search terms of nanoparticle-based biosensors are "biosensors" and "nanoparticle'; While search terms of nanomaterial-based biosensors are "biosensors" and "nano"

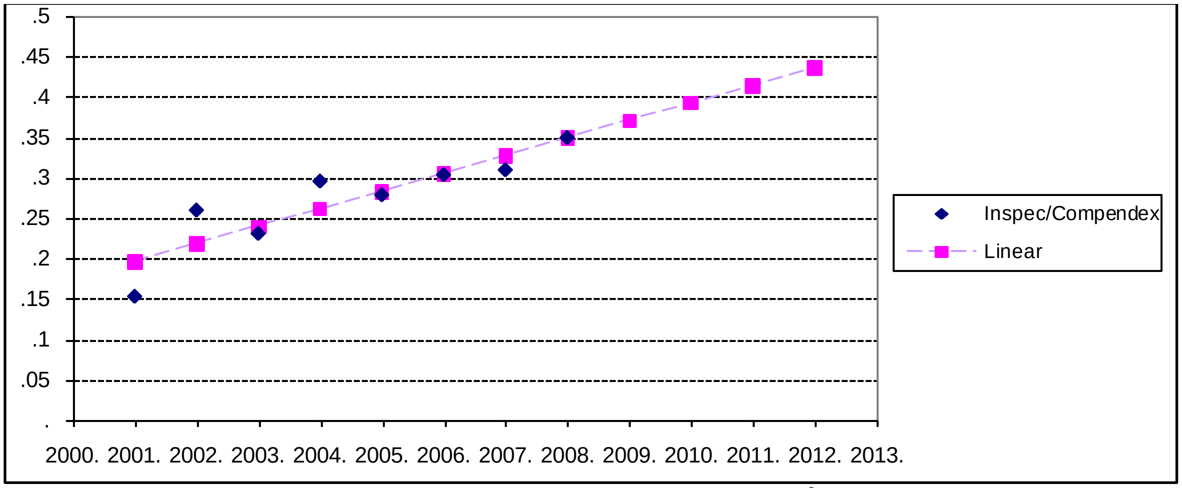

Fig.5: Linear Model adjust to the Bibliometric data[8]

As an emergent field, there has been much interest by the leading countries in research on nanoparticle-based biosensors. This paper not only compares the numbers of publications, but also focuses on the quality and influence of countries in this research field. Citations, as measured by the number of times a paper has been cited, are used here to gauge the level of quality, or impact, of the publications of a country. [This is an imperfect measure, of course, but it is widely accepted as a reasonable indicator that other researchers find worthwhile research knowledge therein (c.f., van Raan, 1988).] The particular analytical method used in this paper focuses on the country location of the affiliation of the first author of the publication. The first author's country is used to assign citation numbers to that country. This focus on the first author is designed to preclude duplicating citation counts.

Another method to be pointed out is that we employ a simple aging practice based on dividing the citations in a given year by the number of years of opportunity to be cited. This is because citations are difficult to evaluate over time. Earlier papers have more occasions to receive citations than do more recent papers (c.f., Youtie, 2008). As for our dataset of SCI, the most recent year is the mid-year of 2008; thus in 2001, papers have 6.5 years of opportunity to attract citations relative to the end-point of our dataset. So the number of citations to papers published in that year is divided by 6.5. Similarly, in 2002, the number of citations should be divided by 5.5; the number 2006 citations is divided by 1.5; and so forth. So, "aged citations" gives us a metric to help gauge change in nations' research publications quality (or impact) over time. Again, this is not a precision measure, but it provides for viable comparison.

In order to make results more robust, we combine the tallies for two-year periods. To reflect the earlier time period, we add 2001 and 2002 together, and compare with the corresponding number for 2005 and 2006 combined. We use 2005-06 to allow a few years for papers to accrue citations. Figures 6 and 7 show the results. A trend line connects the results for (2001 + 2002) to those for (2005 + 2006). Let's consider location on the X axis first. This reflects publication counts. So, in the early time period, the USA is the leader, although the publication counts are modest with 14. However, by the later period, China has taken over the lead in publishing on nanoparticles in biosensors with 158.

The Y axis of Figures 6 and 7 shows the citations received by those papers, adjusted by the years available since publication in which to be cited. So, looking at the starting points of the lines, the US was highest in 2001-02 citation intensity. It remains the leader in the 2005-06 period.

8 Database used: INSPEC/COMPENDEX The limit of Linear Model here is 1.0, and Coeff Det. is 0.79.
The value of the points in the chart represents the ratio of publications counts of nanoparticle-based biosensors divided by publications counts of any nanomaterial-based biosensors. The search terms of nanoparticle-based biosensors are "biosensors" and "nanoparticle'; while the search terms of nanomaterial-based biosensors are "biosensors" and "nano"

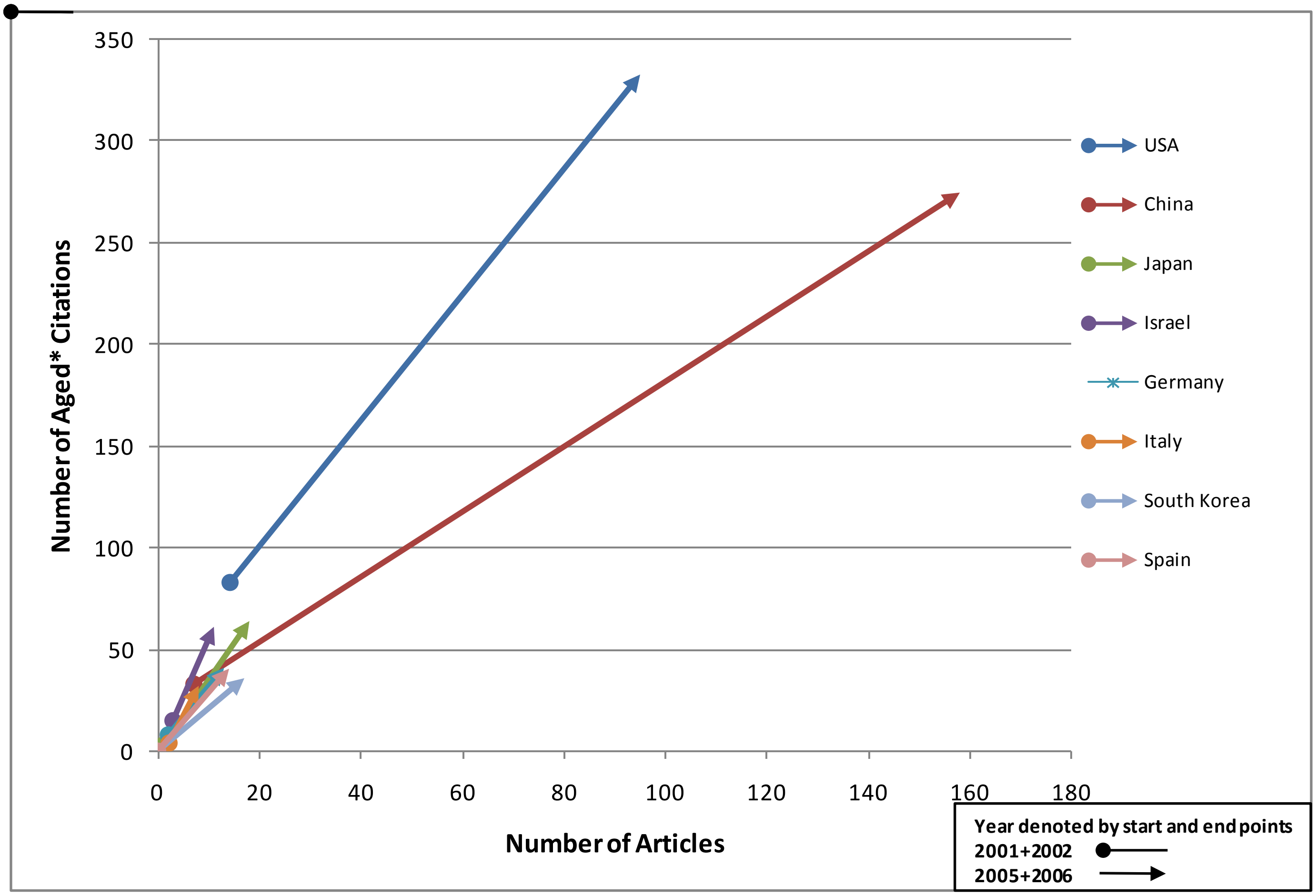

Fig.6: Number of aged citations of nanoparticles applications in biosensor in 2001 plus 2002 and 2005 plus 2006 relative to number of articles of nanoparticles applications in biosensor by first author.[9]

The steeper the slope of the line connecting these two points, the greater the quality orientation of the country has been increasing. From Figure 6, we can find that the US has the steepest slope, suggesting that its nanoparticle-based research receives the greatest attention by researchers. As noted, China is also a leading country in research publication; here we see that Chinese publications also receive increasing citations. Israel, Italy, and Japan have greatly fewer publications and citations than does China ("zoomed in" to see more clearly in Figure 7). However, the vertical slope of their line relative to China suggests that their papers have relatively higher impact. Germany, Spain, and South Korea are also important players in the research on nanoparticle-based biosensors. So any competitive technical intelligence ("CTI") endeavors would also want to monitor their research initiatives.

[9] *Aged citations(AC) for countryi calculated as ACi=Cti/(Yn-Yt) where Cti=total number of citations for articles in target year for countryi; Yn=most recent year in dataset (2008, mid-year); and Yt=target year. For 2001, Yn-Yt=6.5; for 2002, Yn-Yt=5.5; for 2005, Yn-Yt=2.5; for 2006, Yn-Yt=1.5. Country designated by article first author. Database used: Science Citation Index

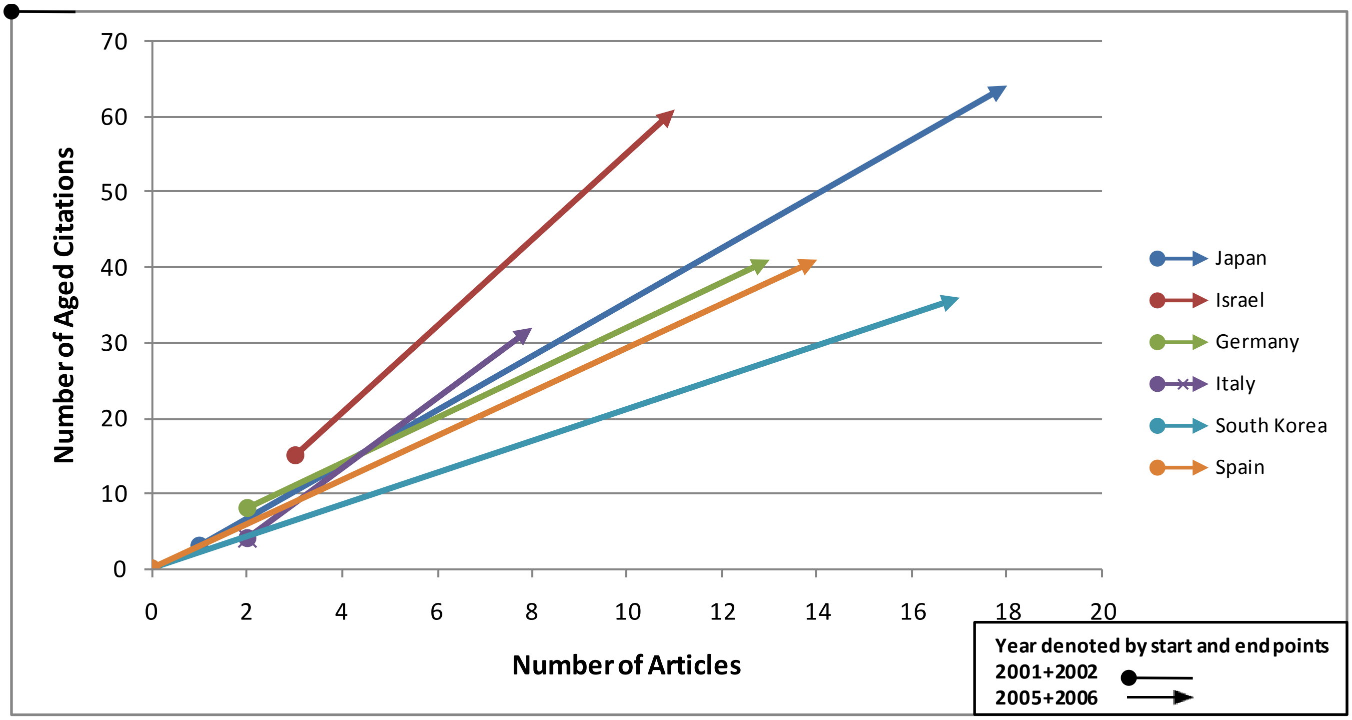

Fig.7: Detailed chart for 6 countries in Figure 6

"Nano" research is highly multidisciplinary (c.f., National Science and Technology Council, 1999; Eto, 2003; Grodal and Grid, 2008; Loveridge et al., 2008; Roco, 2008; Porter and Youtie, under submission). That said, there is considerable discourse as to which fields are importantly involved and the extent to which research knowledge is actively shared among them (c.f., Roco and Bainbridge, 2003; Meyer, 2006). We have found that visualizations of the research fields involved in research, particularly nano research, help one gain perspective on the activity.

Science mapping is emerging as a specialty in its own right (c.f., Chen, 2003; Boyack et al., 2005). We have been developing a "science overlay mapping" approach to locate particular research sets on a base science map (Leydesdorff and Rafols, forthcoming; Rafols and Meyer, forthcoming). This approach uses the Subject Categories that Web of Science assigns to journals. So, for a set of publications indexed by Web of Science (in this case, by SCI, which is part of Web of Science), we locate that research by the journals in which it appears. Figures 8 and 9 do that for subsets of the "nanoparticles and biosensors" research papers, which are based on SCI dataset for 2006 through part-year 2008 in order to focus on the emergent characters of recent 3 years. The base map reflects the 175 Subject Categories shown by the background intersecting arcs among them. The Subject Categories are then grouped into "macro-disciplines" using a form of factor analysis (Principal Components Analysis) based on the degree of co-citation of the Subject Categories in a large sample of articles indexed by Web of Science (Porter and Rafols, forthcoming). Those macro-disciplines become the labels in the figure. The "nanoparticles in biosensors" research concentrations appear as nodes on this map.

These science overlay maps particularly help us answer two questions: which research fields are engaged? how similar is the approach of different players? In this case, we choose to focus on national comparisons. We only show two of the leading countries active in this research arena – the US and China. Some observations:

- Nanoparticles in Biosensors research involves a very extensive range of research fields
- That research is centered in Materials Sciences and Chemistry
- The research also involves a number of Biomedical Sciences
- The Chinese and American research patterns are largely similar – both engage the same broad swath of research fields.
- Chinese and American research emphases are not identical [Table 1 allows one to see significant variations]

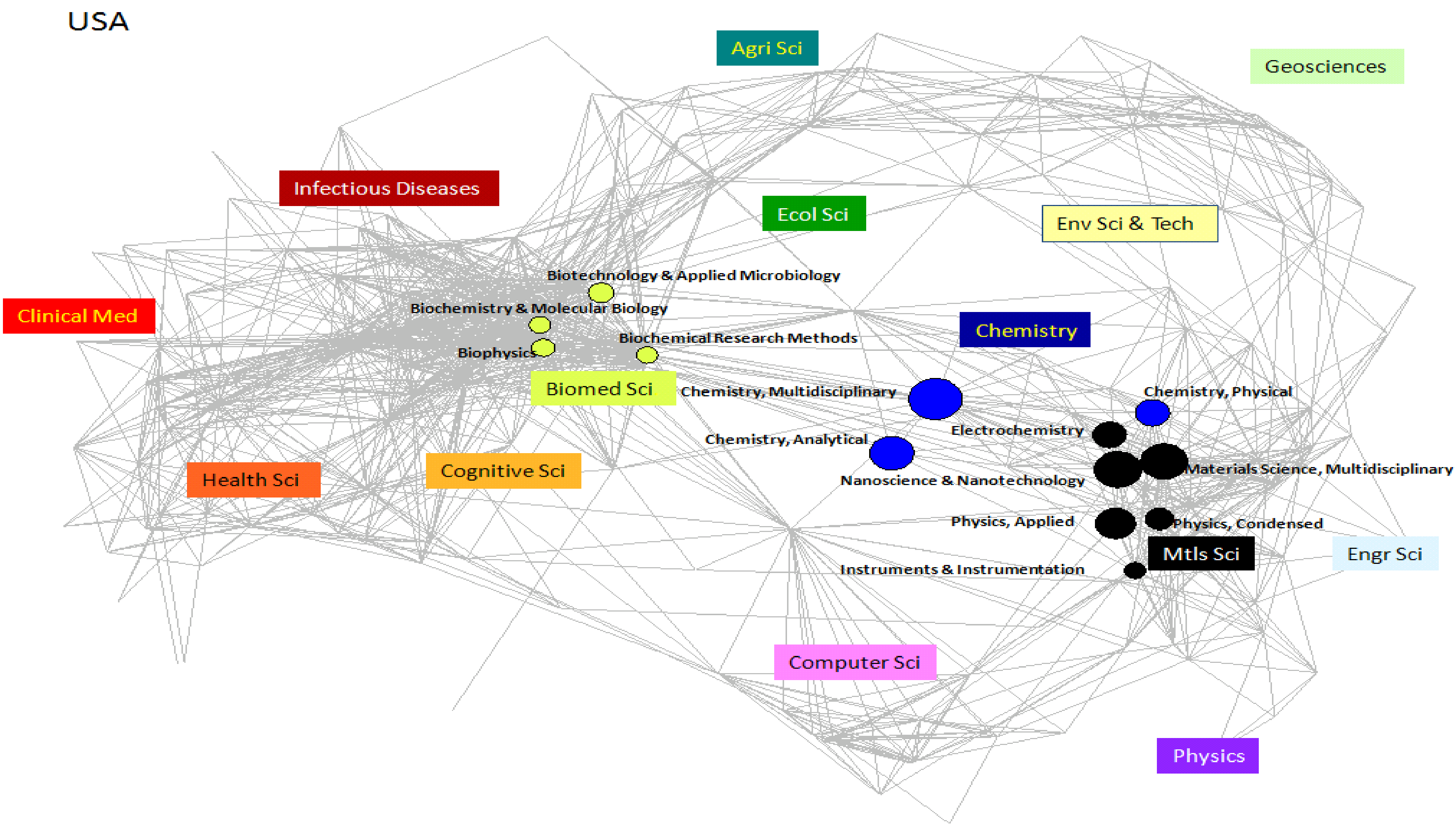

Fig.8: Locating US "Nanoparticles in Biosensors" Research over a Base Map of Science

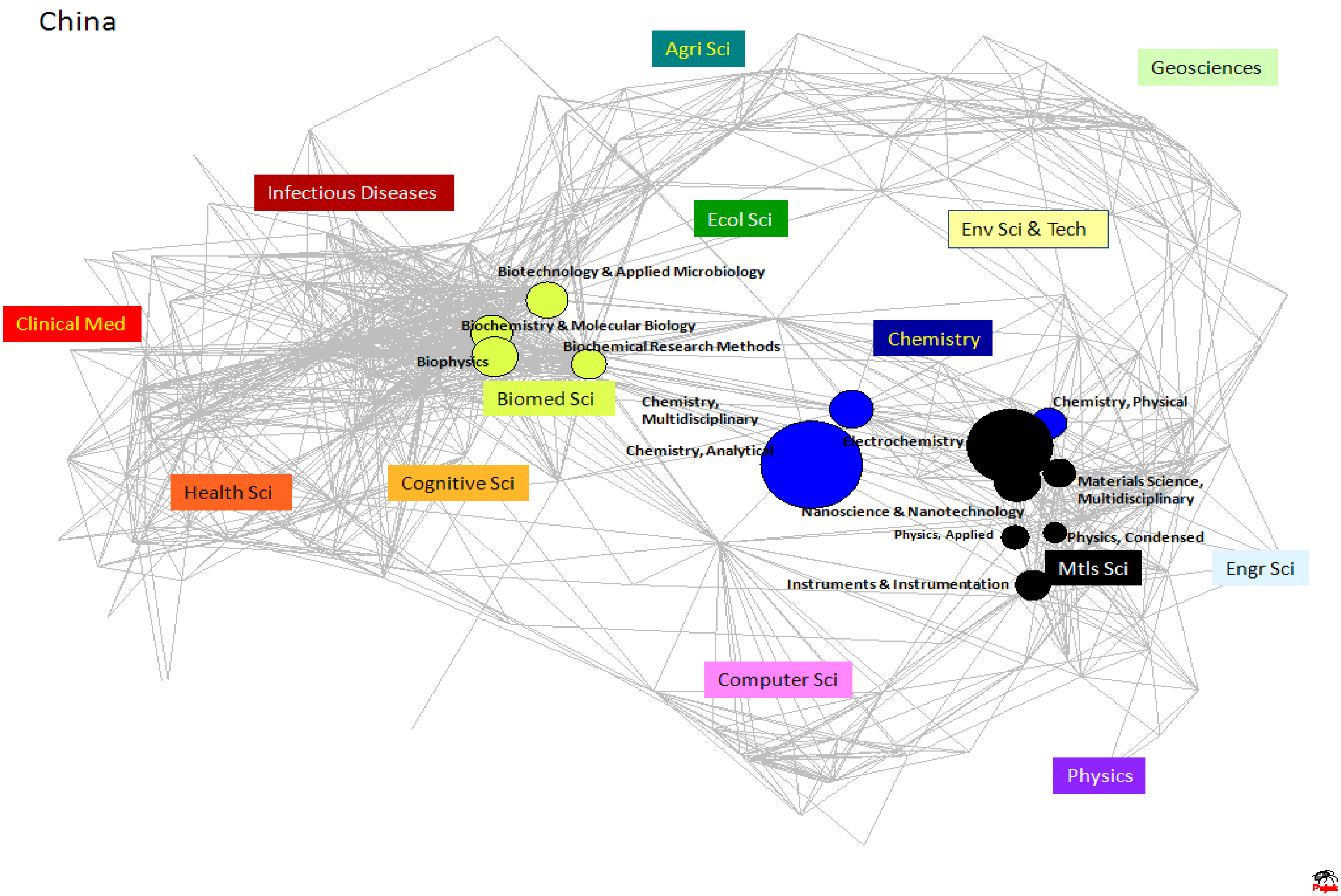

Fig.9: Locating China's "Nanoparticles in Biosensors" Research over a Base Map of Science

Table 1. "Nanoparticles and Biosensors" Research Emphases: USA and China
[Based on SCI dataset for 2006 through part-year 2008]

#		330	141
	Subject Category	**China**	**USA**
328	Chemistry, Analytical	57%	21%
226	Electrochemistry	40%	12%
126	Nanoscience & Nanotechnology	12%	24%
107	Chemistry, Multidisciplinary	11%	30%
101	Materials Science, Multidisciplinary	6%	23%
74	Biophysics	12%	6%
72	Chemistry, Physical	7%	13%
71	Biotechnology & Applied Microbiology	10%	7%
67	Physics, Applied	4%	17%
50	Biochemistry & Molecular Biology	10%	5%
47	Instruments & Instrumentation	7%	5%
42	Physics, Condensed Matter	3%	9%
40	Biochemical Research Methods	7%	5%

Table 1 tabulates the leading Subject Categories represented by Chinese and American publications in this area for 2006-08. On the left, one sees the number of publications associated with each Subject Category. At the top are the number of publications by China and by the USA. The percentages are taken of the national totals. So, for example, 57% of China's articles indexed by SCI for this search set (nanoparticles and biosensors) are associated with Analytical Chemistry journals and another 40% are linked to Electrochemistry. [As you can see, the column percentages total over 100%; that is because Web of Science associates some journals (~39%) with more than one Subject Category.] So, the Chinese research on our topic is heavily Chemistry – much more so than is the American research. Conversely, notice that American articles are considerably more apt to entail Physics sub-areas than are the Chinese. Discerning such differences (and pursuing their implications) can be vital to proactive technology management.

As we know, there are many kinds of nanoparticles used in biosensors. Figure 10 shows the major nanoparticle types widely applied in biosensor systems. In terms of percentage of these four kinds of nanoparticles, metal nanoparticles percentage presents an overwhelming dominion within biosensor research. Before 2002, only metal nanoparticles and oxide nanoparticles were considered in the research for improvement of biosensors. Although semiconductor nanoparticles and composite nanoparticles were employed to enhance the functions of biosensor systems later, these two kinds of nanoparticles are still relatively minor components of this research domain.

We can probe a level deeper. Metal nanoparticles constitute a big family, including Pt, Ag, Au, Pd, Cu nanoparticles and so on. This could be a major reason for its high profile in nanoparticle-based biosensors. Turning to the publications counts of typical nanoparticles in metal nanoparticles applied in biosensors (Figure 11), we can conclude that gold (Au) nanoparticles are the most frequently used among all the metal nanoparticles in biosensor systems. The gold nanoparticles publications count has kept increasing from 2001 to 2008. However, the other two metal nanoparticles are becoming popular in the research on biosensors in recent years. Platinum nanoparticles, particularly, present as an emerging nanoparticle which is increasingly popular since 2007 in constructing biosensors.

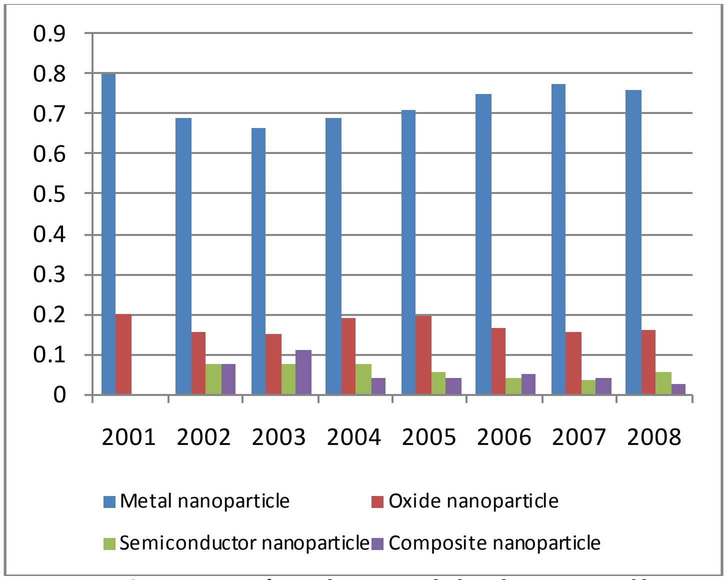

Fig.10: Percentage of annual Nanoparticle-based Biosensors publications by nanoparticle type. Databases used: Science Citation Index, 2001-2008(estimated)

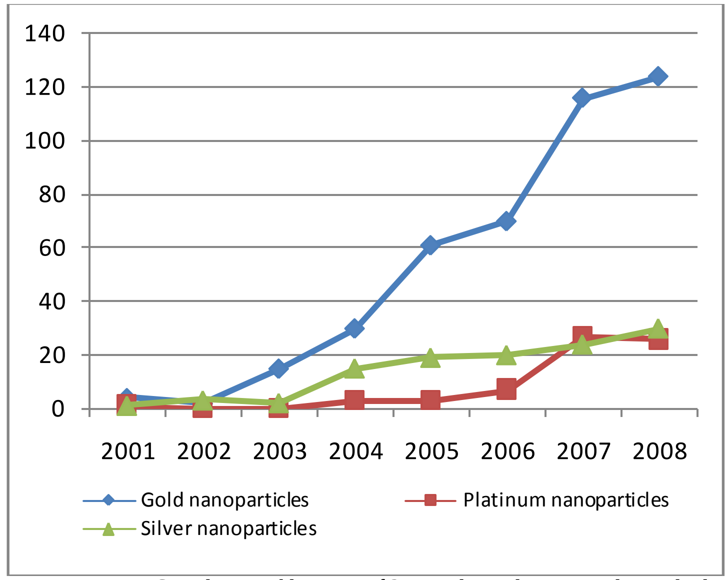

Fig.11: Cumulative publications of 3 typical Metal nanoparticles applied in biosensors. Databases used: Science Citation Index, 2001-2008(estimated)

As for the prominent research fields of nanoparticle-based biosensors, we selected top 6 kinds of biosensors according to their publications numbers in our SCI dataset. In order to capture the character of this research, we focus on the most recent 3 years (2006 through 2008 mid-year). Figure 12 shows that the publications counts of these 6 nanoparticle-based biosensors are increasing year by year. Electrochemical biosensors are at the top followed by glucose biosensors, amperometric biosensors, enzyme biosensors, hydrogen-peroxide biosensors, and optical biosensors.

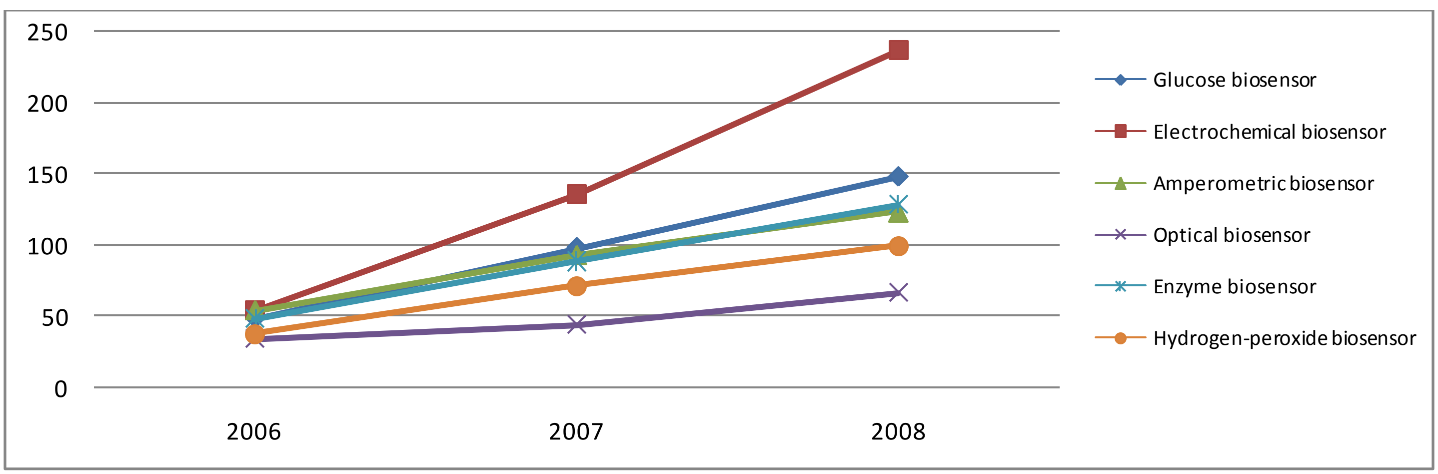

Fig.12: Cumulative publications of Top 6 Nanoparticle-based Biosensors in recent 3 years
Databases used: Science Citation Index, 2006-2008(estimated)

Nowadays, more and more researchers attend to the studies of biosensors based on nanoparticles. Our search results show that biosensors composed with nanoparticles do purport to provide advantages in their sensitivity, stability, accuracy, selectivity, and so on. Furthermore, these nanoparticles play different roles in different biosensor systems based on their unique properties. For instance, biosensors with improved stability can be prepared using nanoparticles as substrates for biomolecule immobilization. Additionally, biosensors with enhanced sensitivity and selectivity can be developed making use of the catalytic properties of nanoparticles. Table 2 takes the case of gold nanoparticles, addressing the main functions noted in our article set, and examining the advantages for related biosensors.

Table 2. Different functions of gold nanoparticle in different biosensor systems

Functions	Biosensor	Sensor advantages	Typical examples
Biomolecule immobilization	Amperometric biosensor	Improved stability	Bienzyme amperometric biosensor using gold nanoparticle-modified electrodes for the determination of inulin in foods (c.f., Manso J , 2008).
Catalysis of reactions	Glucose biosensor	Improved sensitivity and selectivity	Glucose biosensor based on Au nanoparticles (c.f., Xian YZ, 2005).
Labeling biomolecules	Optical biosensor	Improved sensitivity Indirect detection	Self-assembled nanoparticle probes for recognition and detection of biomolecules(c.f., Maxwell D.J, 2002).
Enhancement of electron transfer	Electrochemical biosensor	Improved sensitivity Direct electrochemistry of proteins	Colloid Au-enhanced DNA immobilization for the electrochemical detection of sequence-specific DNA(c.f., Cai H, 2001).

Due to its large specific surface area and high surface free energy, gold nanoparticles can adsorb biomolecules strongly and play an important role in the immobilization of biomolecules in biosensor construction. In addition, the combination of the catalytic properties of gold nanoparticles with the unique properties of biosensors can result in the construction of highly sensitive sensor systems. We are quickly reaching beyond our limits of technical knowledge! We present these data to suggest to technology analysts and managers the potential to generate valuable CTI. And again, we reiterate that engagement of technical experts is essential to identify the nuances and implications of such empirical information.

Conclusions and Future Perspectives

This paper has examined R&D on nanoparticle-based biosensors and employed bibliometric analyses as a means to help forecast R&D trends and identify the emerging nanoparticle roles in biosensors. According to the results of the trend analysis with growth models, the R&D activities of nanoparticle-based biosensors appear likely to increase over the next few years. Moreover, nanoparticles show greater potential to improve biosensors than do other nanomaterials. This could help focus technology managers attention on this portion of nano research activity.

In addition, a combination of quantity (publication) and quality (citation) analysis for nanoparticle-based biosensors helps position the leading countries in this research field. Science overlay mapping helps us see the different emphases of nanoparticle-based biosensors research between the US and China. Technology managers might well want to extend such analyses to profile the research emphases of particular organizations. By identifying particular specializations and research strengths, they can identify potential technology development partners. Such research outreach is becoming increasingly essential as "Open Innovation" becomes increasingly important (c.f., Chesbrough, 2006; Huston and Sakkab, 2006). This is especially so in today's difficult economy.

Researchers tend to combine nanoparticles into the materials used for biosensors in order to improve the sensitivity of the system in potential sensing applications. In recent years nanoparticles relating to biosensors show significant maturation. In particular, we analyze the increasing focus on specific nanoparticle-based biosensors functions. These include major nanoparticle-based biosensors, such as glucose biosensors, electrochemical biosensors, enzyme biosensors, optical biosensors, and amperometric biosensors. One type of nanoparticle can play different roles in different biosensor systems, and it can also play more than one role in the same biosensor system. Our observation that "nano in biosensors" research has become increasingly specific – in terms of particular materials and particular functional gains – is a key indicator that this technology is "emerging" (c.f., Watts and Porter, 1997). When research shifts from the general to the specific, this is a key benchmark of maturation.

We looked into the applications of gold nanparticles in different biosensors, and a future course of investigation would involve developing enhanced methods for mining the basic and special functions of different types of nanoparticles in biosensor systems.

Nanoparticle-based biosensor system is a highly cross-disciplinary research arena. This suggests value in exploring the relationships further. Is research concentrated in other Subject Categories being fully utilized by researchers in other domains? What is the cooperative research network? For instance, are there conferences to bring together the biomedical researchers with the chemists, with the materials scientists, and the physicists, to share cutting edge knowledge that could come to bear on nano-enhancement of various biosensors? For the technology manager, what can you do to facilitate cross-field and cross-institutional research knowledge transfer? Our "outsider" perspective, based on these bibliometric analyses, is that this field is ripe for stimulated research knowledge exchange. The variety of nanoparticles, multiple functions, and diverse applications suggest that R&D managers should actively reach out and exploit cross-area results.

In closing, we note an important caution. Before basing technology management decisions on such a forecast, one would want to obtain expert opinions by researchers and business people conversant with the topic. These empirical results should be reviewed by knowledgeable professionals to check that they correctly represent what is happening in the research labs. And if so, experts can help build upon these results to suggest additional linkages to related research domains to explore. And if not, the experts can help refine the searches and refocus the inquiry to better understand patterns in such an emerging technology.

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