

Current trends in nanotechnology research across worldwide geo-economic players

Mario Coccia · Ugo Finardi · Diego Margon

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Abstract The purpose of this paper is to analyze the current temporal and spatial trajectories in nanotechnology research in order to display the worldwide patterns of scientific domains across main geo-economic players. Current trends of nanotechnology have been growing in chemistry and medicine because of technological applications of new nanomaterials mainly in Chemical Engineering, Biochemistry, Genetics and Molecular Biology. In addition, the results show that the laboratories of Europe and North America have intensive scientific collaborations with foreign scholars in nanotechnology studies. This paper can provide vital findings to support new research and innovation policies in order to foster the development of these driving converging technologies for future patterns of economic growth.

Keywords Nanotechnology · Technological trajectories · Research trends · Data mining · Comparative innovation systems

JEL Classifications L6 · O3 · Q57

M. Coccia · U. Finardi · D. Margon
CNR-National Research Council of Italy, CERIS-CNR, via Real Collegio, n. 30,
10024 Moncalieri, Torino, Italy
e-mail: m.coccia@ceris.cnr.it

D. Margon
e-mail: d.margon@ceris.cnr.it

U. Finardi (✉)
Dipartimento di Chimica I.F.M. and NIS—Centre of Excellence, Università di Torino,
via P. Giuria 7, 10125 Torino, Italy
e-mail: ugo.finardi@unito.it

1 Introduction

The “birth certificate” of nanotechnologies, from the conceptual point of view, is considered the talk by Richard P. Feynman at the American Physical Society meeting held at California Institute of Technology in 1959, where the Nobel Prize Laureate in 1965 uttered the famous sentence: “There is plenty of room at the bottom” talking about the opportunities for science and technology given by the vast expansion of scientific and technological research towards the nanometric dimensional range.

Renn and Roco (2006, p. 154) argue that: “Nanoscience is the result of interdisciplinary cooperation between physics, chemistry, biotechnology, materials science and engineering towards studying assemblies of atoms and molecules”. Roco (2007) also argues that nanotechnology trajectories are characterized by high level of exponential growth that will generate new radical and incremental innovations in not-too-distant future. Nowadays the nanotechnologies, as “converging technologies” (Bainbridge and Roco 2006, *passim*), are ones of main determinants of modern patterns of technological innovation, and nanotechnology dynamics is fully inserted in the paths of “creative destruction” generated by Information and Communication Technology Wave (cf. Freeman and Soete 1987; Bozeman et al. 2007; Coccia 2010a, b). For this reason, there is a vital interest to analyze the technological trajectories of nanotechnology and the specificity of countries in nanotechnology production and its application in order to forecast research trends and future effects onto industrial dynamics across countries (cf. Coccia et al. 2010; de Miranda Santo et al. 2006; Goddard III et al. 2007; Leydesdorff and Zhou 2007; Salerno et al. 2008).

The purpose of this essay is on current technological and scientific trajectories of nanotechnology across worldwide economic players. In particular, considering the theoretical background of the economic literature, we assert the following hypotheses:

Hp. 1 Nanotechnology research activities have been increasing in applied research fields, and mainly in life science applications;

Hp. 2 The interaction of nanotechnology research has been increasing across geo-economic players.

The purpose of this research is to verify these hypotheses by empirical evidence based on codified scientific production of different geo-economic regions over time to probe *how* they have been acting and reacting towards nanotechnology studies, and *how* they have been behaving in the international collaboration in nanotechnology research. This research can provide main findings in order to explore the current worldwide research trends in nanotechnology that support modern innovations able to drive future patterns of economic growth. Next section exploits the research strategy to test our hypotheses.

2 Strategy of research

The spreading of nanotechnology in basic sciences and in technological applications has caused the insurgence of great interest towards their study by economics of science and innovation (cf. Bozeman et al. 2007). Scientometric approaches are effective techniques to analyze the emergence and development of research fields in nanotechnology (Braun et al. 1997). Salerno et al. (2008) argue that: “Bibliometric analysis of publications [...] can help have a synthetic picture of the best players at a worldwide level, their lines of inquiries and their relationships, that is, they could help to cope with the extremely fragmented

knowledge, actors and applications involved in the evolution of the field” (p. 1220).¹ This paper uses the dataset of Scopus (2011)² and data mining is performed by:

- (a) the search of “nano*” on “Article Title, Abstract, Keyword” and a further refinement by the following keywords: “Nanostructured materials”, “Nanotechnology” or “Nanostructures”, in order to capture all scientific output in these topics.
- (b) Time Horizon from 1996 to 2008 (Note that Scopus starts gathering full data in 1996).
- (c) Key geo-economic areas: USA and Canada, South Korea, Japan, China and Europe. These geo-economic areas are the main worldwide players in the production of nanotechnology and nanoscience studies.

According to Porter et al. (2008), there is need to be clear about the intended uses of the nanotechnology datasets (p. 720), given the multidimensional character, the cross-disciplinarity and the ill-defined borders of nanotechnology (p. 726). Our dataset derives from a data mining that can be placed in the subset of Boolean methodologies (cf. Porter et al. 2008, p. 717ff). The selection of three most representatives, general and safely nanotech-related keywords (described above in the point *a.*) provides a complete dataset for our analysis, which is aimed at methodological simplicity, confidence of results and inclusivity.

In particular, the dataset contains the *affiliations* of authors (i.e. main research institutions and/or labs where the research is carried out by scholars) and the *subject areas*³ of journals where nanotechnology research is published, that are a strong indicator of the content of the scientific output. The sample is based on the 149,324 scientific products (e.g. Articles, Proceedings, etc.) about nanotechnology research with their affiliations (about 96% of main research labs operating in nanotechnology). As papers are published on journals that are classified per 28 subject areas, the 149,324 scientific products have almost 400,000 occurrences of subject areas. In general, the number of occurrences of subject areas by articles is greater than the total number of papers.⁴ The occurrences of articles per subject areas show how much attention some nanotechnology topics have received in the scientific literature. In order to avoid distortions of data, because of overlap by subject areas per paper, they have been aggregated in “Macro Subject Areas”: Materials Science, Chemistry and Medicine, Physics and Earth Sciences, Engineering. This aggregation is important to show the temporal and spatial pattern of nanotechnology research trends across countries. This methodology should avoid both the sampling of data not meaningful for the research and the biasing due to the selection of more specific keywords that could be related to localization of specific research activities in particular geographic areas.

In particular, the more detailed analysis per keywords has not been considered first of all because of the high number of generic keywords in data mining, like “Synthesis”, “Chemistry”, “Priority journal”, “Crystallization”, “Methodology” etc. Moreover keywords do not refer necessarily to a specific research field, making such an analysis less

¹ The literature is vast and not fully cited here, but a good list of references is found in Kostoff et al. (2006, 2007a, b); Shapira and Youtie (2008); Huang et al. (2011).

² <http://info.scopus.com/about/> (accessed March 11, 2011); See also <http://info.scopus.com/why-scopus/academia/> (accessed June 18, 2010).

³ Scopus classifies journals in major subject areas. Journals can be allocated to multiple subject areas as appropriate to their scope. We use all subject areas containing papers on nanotechnology research.

⁴ For instance a paper about nanotechnology published on the journal *Scientometrics*, is one paper with 3 subject areas, since *Scientometrics* is classified by Scopus with three subject areas (computer science applications, social sciences and library and information sciences).

meaningful. In fact, the categorization of research domains in “nanomaterials”, “nanoelectronics”, etc. has not been considered because there are inner overlaps across scientific nano-research: e.g. nanomaterials are heavily applied in nanoelectronics; therefore considering this categorization is not fruitful for investigating the real nanotechnology research trajectories and could bring to ambiguous results and misleading research trends. Vice versa, the aggregate sets, applied in this essay, provide more accurate and robust results about the temporal and spatial research trends. Our methodology has been verified to be more reliable under these points of view. In addition, this approach is comprehensive on large scale and provides main information about several characteristics of scientific products in nanotechnology research.

Another main scientometric analysis performed is the scientific interaction in nanotechnology research across geo-economic areas. We consider in each geographical area, for its scientific output, the foreign affiliations in nanotechnology research in order to count the mutual scientific collaboration for nano-research with other countries. The analysis of our vast sample is carried out by statistical and graph analyses considering some critical research fields and geo-economic areas in order to show the driving trends and collaborations in nanotechnology research.

3 Empirical evidence of hypotheses and discussion

The structure of domestic research labs in nanotechnology shows that the highest number over 1996–2008 is in Europe and North America (i.e. USA and Canada): about 150 research centres operating in nanotechnology fields in 2008. Japan has a lower number of research labs, roughly 100 units. Nanotechnology research centres have been increasing in China and South Korea⁵: China has more than 130 nanotechnology research labs operating in 2008. As the absolute numbers of scientific products across geo-economic areas are not suitable values for reliable spatial and temporal comparisons (because the research trends have similar paths), we compute relative values (percentage) to analyze the mutual temporal dynamics within nano-research fields in 1996–2008 period. Although nanotechnology research in Materials science has a higher absolute scientific production in comparison with other macro subject areas (see Table 2 in “Appendix”), the knowledge dynamics shows mainly a substantial relative reduction over time and space in Materials science, whereas nano-research in Chemistry and Medicine has been increasing. Instead, nano-science studies in “Physics and Earth Sciences” have roughly a relative steady declining trend across geo-economic areas. Nano-research in Engineering sciences has also a steady growing trend across geo-economic areas. Figure 1 displays the trends of nanotechnology research, from 1996 to 2008, across all worldwide geo-economic areas. In particular, nano-research in “Chemistry and Medicine” has been increasing in the last 15 years with a relative high rate of growth, due to the high number of applications (innovations) in Chemical Engineering, Biochemistry, Genetics, Pharmaceuticals, etc. (cf. Fig. 2). These vital results support the statement of Hp. 1.

As far as the nanotechnology research in “Materials science” is concerned, the leading productive countries are mainly Europe and China over 1996–2008 period, although the relative role of China has been increasing over 2002–2008. Other macro areas, i.e. “Physics and Earth Sciences” and “Engineering”, show the leadership of Europe and USA-Canada.

⁵ Cf. de Miranda Santo et al. (2006), pp. 1022ff.

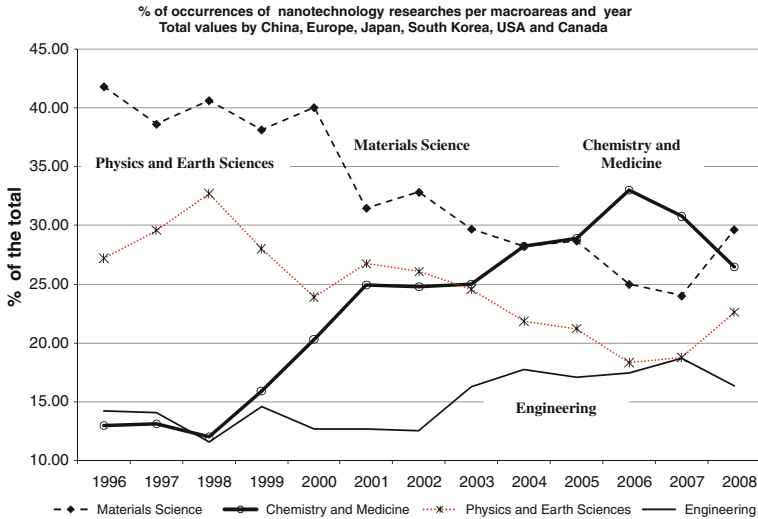


Fig. 1 Current trends in nanotechnology research (% values) per macro subject areas

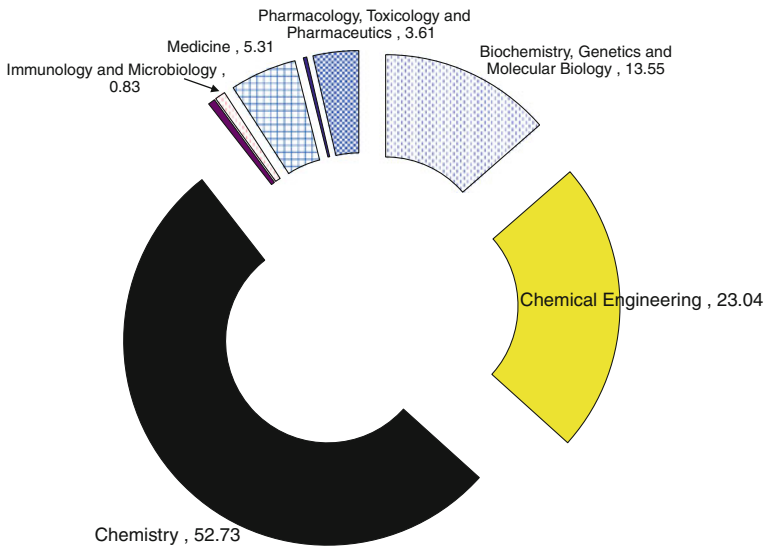


Fig. 2 Percent value of main research fields of nanotechnology in chemistry and medicine

A main result to support the Hp. 2 is showed in Fig. 3 on the mutual scientific interaction across geo-economic areas in nanotechnology research. Although each geo-economic area has a vast production of scientific outputs within domestic nanotechnology research centres (about 90%), the 10% is carried out in collaboration with foreign research centres. In particular, the analysis shows the following main findings: labs of Europe and USA-Canada have a high capacity of attraction of collaborations with foreign scholars in the scientific research on nanotechnology, measured by joint affiliations in papers (see the simple bars above the x-axis in Fig. 3), whereas South Korea and China are the two

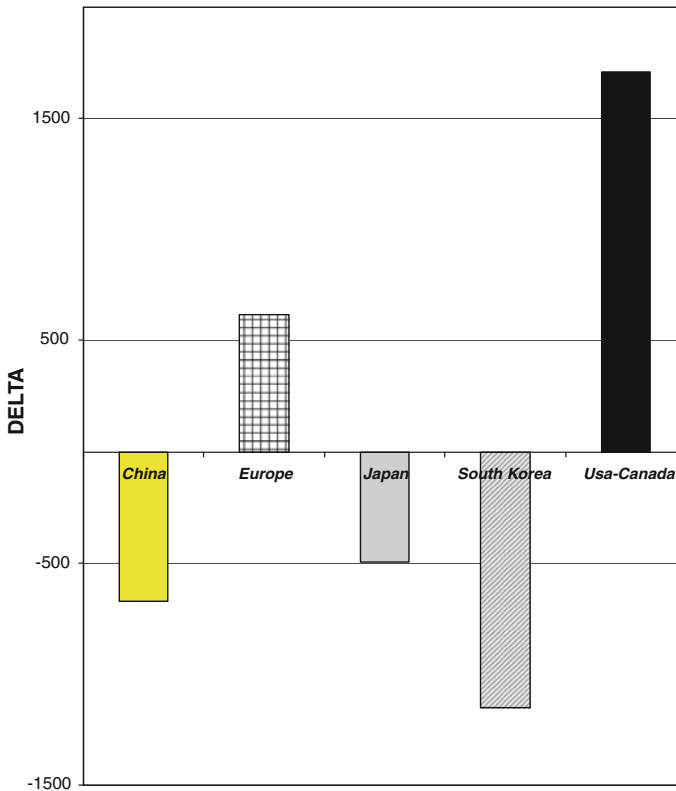


Fig. 3 Research attraction capacity of foreign scholars in nanotechnology research per geo-economic areas, 1996–2008 period. *Note:* Delta is the difference between: (nano-research products by scholars of other geo-economic areas in collaboration with research centres/scholars located in the country A) and (nano-research produced in research labs of the country A with foreign institutions/scholars); positive Delta means high attraction capacity in nanotechnology research by the specific country, vice versa negative Delta means country with intensive collaborations in nanotechnology research with foreign labs

geographic areas having the highest number of scientific collaborations with other economic players in nanotechnology research.

The results of this research raise some vital questions:

Why nano-research trend in “Chemistry and Medicine” has been increasing, while “Materials Science” research has been decreasing?

Results on the temporal relative decrease of nano-research in “Materials science” and increase in “Chemistry and Medicine” can be due to knowledge dynamics of nanotechnology research that has been passing from technology trajectory focused on inventions of new nanomaterials to innovative applications in biochemistry, medicine, genetics, and so on. In other words: some inventions of nano-materials have been becoming radical and incremental innovations applied in several fields such as chemical engineering and medicine, such that nano-knowledge dynamics has been evolving from invention to innovation phase. In fact, Shapira et al. (2011) also show that the transition process, from discovery to application in nanotechnology, may be underway in large corporate (p. 7).

Some interesting examples of these facts exist. The most trivial is the use of silver nanoparticles, exploited as anti-bacterial in fabrics. In addition, nanostructuring of

materials in textiles plays a main role as anti-biotic, anti-static, anti-ultraviolet, water repellent moisture management and self-cleaning garments. The domain of nanoelectronics is another example, where, benefiting from novel techniques, circuitry is nowadays reduced well below the 50 nanometer (symbol nm equal to one billionth of a metre) dimensional range in order to obtain faster and more efficient performances. Another example is the application of nanotechnologies in Life Sciences, such as biocompatible-materials-made of nanoparticles that are applied for targeted therapy (drug delivery) against cancers of the human body. Such nanoparticles are starting to be exploited in clinical practice, while patenting activities for this subject have grown steadily since the beginning of 2000s.⁶

Nevertheless, as Rafols et al. (2011, p. 4ff) note, nanomaterials are not generally consumer products that are sold to end users, but they are incorporated into other products manufactured in a variety of industries, in order to improve the quality of commercialized products into markets. Meyer (2007, p. 799ff) also underlines that the current typology of technological change in nanotechnology is incremental rather than radical. In fact, his analysis shows that companies tend to develop nanotechnology applications within their typical products rather than bring out new products.

Under this point of view an interesting example is the application of nanotechnologies to hydroxyapatites.⁷ Such materials are currently used as fillers in bone-repairing surgery in both orthopedic and dental fields because of their biocompatibility and re-absorbability capacity. Nano-structuring of these materials improves the quality of orthopedic prostheses. These facts make it more difficult to identify the presence of nanostructured materials in commercialized products, and thus to discover and study them.

Our main results are corroborated by findings of other scholars on patent settings. Recently, Thursby and Thursby (2011) show evidence that academic patenting in nanotechnology and biotechnology has a strong support by industry R&D, in comparison to other scientific fields (p. 16). Mangematin et al. (2011) find that large companies are developing nanotechnology research by their subsidiaries that generate spillovers within the holding for supporting the overall technological innovation process (p. 12ff). Instead, Islam and Miyazaki (2010) argue that: “US has gained much strength in bio nanotechnology research relative to other domains, and the other regions (e.g. the EU, Japan, China, South Korea and India) have gained their research strength in nanomaterials, nanoelectronics and nanomanufacturing and tools” (p. 229).

In this dynamic setting for nano-research,

Which is the high performer national system for nano-technological production?

Figure 4 shows that the development curve of nanotechnology production is not linear, but *S-shaped*⁸ over 1996–2008, and also the relative higher number of scientific outputs per

⁶ A simple query performed in the Scopus SciVerse database (which obtains data from EPO's Espacenet database) for the keyword “nanoparticle AND drug delivery” rendered a number of occurrences going from 311 to 3,843 over 2000–2009 period.

⁷ Hydroxyapatites or Hydroxylapatites are a class of materials, also occurring in nature, whose chemical composition contains Calcium atoms and Phosphate groups, together with hydroxyls. As a high percentage of human bone is made of a modified form of the mineral, hydroxyapatites are also widely exploited as a filler or coating for prosthetic implants.

⁸ Roco (2007) argues that nanotechnology trajectories are now in the first phase of the *S-shaped* curve of growth, i.e. before the point of inflection and conjectures that the dynamics of nanotechnology outcomes will pass the point of inflection after the year 2020 or thereabouts.

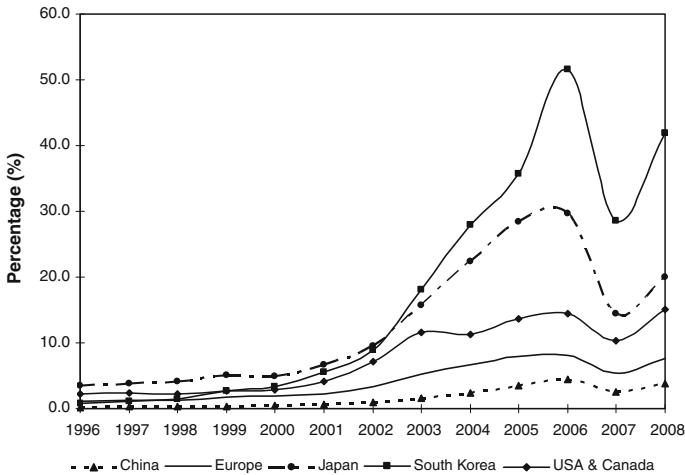


Fig. 4 Scientific products in nanotechnology per million people across geo-economic areas over 1996–2008

Table 1 Research investments and scientific performance in nanotechnology research across leading geo-economic players

Countries	Specific. Nanotech R&D 2004 (\$/Capita)*	Nanotechnology scientific products per million people 2004	Nanotechnology scientific products per million people 2008
USA	3.7	11.28	15.07
Europe	2.3	6.62	7.65
Japan	7.4	22.30	19.93
China	0.2	2.40	3.80
South-Korea	6.2	27.92	41.98

* Source: Roco (2007), pp. 3.1–3.26

million people in South Korea and Japan. A critical point is 2002 when the increasing trend of South Korea has been prevailing on Japan and other geo-economic players. In addition, Table 1 shows that R&D investment in nanotechnology as \$/capita is 6.2 in South Korea, lower than Japan (7.4). However, nano-research outputs in South Korea are 27.92 scientific products per million people, a value higher than Japan (22.30). This gap is higher if the scientific performances of 2008 are considered: 41.98 scientific products (in nanotechnology) per million people in South Korea versus 19.93 in Japan. Therefore, these results show that the specificity of national system of nanotechnology in South Korea has higher performance in comparison with Japan and other geo-economic areas. However it is important to note that the scientific collaborations in nano-research show that Europe and North America have a high attraction capacity of collaboration in nanotechnology research with scholars from other geo-economic areas (over 1996–2008).

Other scholars show results going in the direction of our findings. Shapira et al. (2011, p. 16) analyzing patent data, find significant differences between national systems of innovation in nanotechnology: behind the leading role of USA, Japan and European countries (Germany, France and UK), South Korea and China show an increase in patent

applications in nanotechnology; in fact, innovation system policies, triple helix linkages and national context (e.g. academic institutions, finance, manufacturing sectors) are important in affecting nano-research trajectories.

Miyazaki and Islam (2007, p. 665), exploiting journal article data up to 2004, affirm that USA regain, in the 2000s, a leading position in nanotechnology over Europe through the massive investment in the National Nanotechnology Initiative. Their analysis also shows that Japan was yet loosing its leadership in Asia in comparison to other countries, whereas China has an acceleration in nano-research production. Li et al. (2008), performing a longitudinal analysis from 1976 to 2005, also find a rapid growth of China (since 1995) and South Korea (since 2000). Youtie et al. (2008) confirm that Asian countries have been increasing publications over time (but their analysis stops in 2006). Instead, Huang et al. (2011, p. 154) show that US had a leading position in the past, followed by Europe and Japan, while nowadays new players (such as China and South Korea) have been increasing their role in the worldwide nano-research production.

In conclusion, this paper has explored main worldwide trends of nanotechnology research, and main lessons learned are:

- Nanotechnology has been growing in life science applications because of transition of nano-research from invention of nanomaterials to innovation phases in life sciences.
- Worldwide leading nano-research is polarized around North-America and Europe geo-economic areas.
- Growing role in nano-research production by South Korea and China.

However the results could have some limits. The main one is that Scopus retrieves the first 160 results for each item (Source, Affiliation, Keyword, etc.); in addition, Scopus is a relatively new instrument for scientific literature classification and not all nanotechnology research might be included (though this limit is common with other web-based datasets). It is important to note that scientometric analysis for trends and scientific collaboration in nano-research is a hard work since these new technologies are characterized by “inter-disciplinarity” and “pervasiveness” research and innovation (Salerno et al. 2008, p. 1206, 1208, and 1220, *passim*) and by growing fusion of trajectories between traditional sectors (cf. Islam and Miyazaki 2009, p. 139).

In presence of these scientific and analytical issues, further research about the trends in nanotechnology is needed in order to design provident innovation policy supporting these new “converging innovations” (Bainbridge and Roco 2006) that may drive the future paths of growth of economies in turbulent markets (cf. also Coccia 2010a).

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with a focus on research and industrialization of new materials and technology transfer. *Diego Margon* is a technician at the National Research Council of Italy (Cnr-CNR). He is specialized in data collection and data analysis applying statistical software packages, and has published several technical reports about technological topics.

Appendix

See Table 2.

Table 2 Scientific output in nano-research over 1996–2008 per subject areas and macro subject areas

Macro Subject Area (S.A.)	Subjects area (S.A.)	Papers in S.A.	*Total papers in Macro S.A.	%
Materials science	Materials science	117,808	117,808*	29.46
Chemistry and medicine	Biochemistry, genetics and molecular biology	14,471		3.62
	Chemical engineering	24,617		6.16
	Chemistry	56,329		14.09
	Immunology and microbiology	889		0.22
	Medicine	5,677		1.42
	Neuroscience	336		0.08
	Pharmacology, toxicology and pharmaceuticals	3,855		0.96
	Minor subject areas	660	106,834*	0.16
Physics and earth sciences	Earth and planetary sciences	1,555		0.39
	Physics and astronomy	88,418	89,973*	22.11
Engineering	Engineering	65,421	65,421*	16.36
Others	Information sciences, energy, environment science	19,795	19,795*	4.97
Total		399,831	399,831*	100.00

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