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International collaboration development in nanotechnology: a perspective of patent network analysis

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Abstract International collaboration has played an important role in the development of nanotechnology. Patents encompass valuable technological information and collaborative efforts. Thus, this paper examines international collaboration development in nanotechnology using patent network analysis. The results show that the number of international collaboration nanotechnology patents has increased steadily and the proportion of them of total nanotechnology patents has likewise exhibited an upward trend. USA has always been the most influential participant with largest number of international collaboration patents. Asian countries/regions have shown an obvious increase in the number of international collaboration patents. By contrast, there have shown a generally decline in European countries. More and more countries have become actively engaged in international collaboration in nanotechnology with increasingly closer relationships. Two styles of international collaboration exit: while USA, Germany, UK and Japan collaborate with a wide range of countries/regions; Spain, Israel, Russia, Singapore and Taiwan are more selective in their collaboration partners. Though International collaboration has yet to find global significance in terms of patent citation impacts, it has nevertheless been incremental in improving patent citation impacts for most of the top 20 countries/regions since 2004.

Keywords Nanotechnology · International collaboration · Patent · Network analysis

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Introduction

Nanotechnology is commonly considered as promising in a wide-range of high-tech sectors, especially in the context of pressing global challenges such as those related to energy, health care, clean water and climate change. Many countries, with investments from governments, have devoted in the research and development (R&D) in nanotechnology. Companies and research institutes have also been engaged. In recent years, advancements in science and technology (S&T) are no longer confined to the S&T advancement of individual nations (Graham and Thomas 2000; Melkers and Kiopa 2010; Chang 2012). Many countries have actively promoted international collaboration to share knowledge, generate projects and participate in research communities (Sin 2011; Graham and Thomas 2000; Melkers and Kiopa 2010). As a rapidly developing and emerging field, nanotechnology requires extensive international collaboration to foster more efficient development outcomes. Thus, this study analyzes the characteristics and the evolution of international collaboration of nanotechnology in a global context, in hope of providing an objective reference for future policy-making, which may help governments find influential partners to utilize resources worldwide and compete in the R&D of nanotechnology globally.

In response to the growing importance of nanotechnology, several studies have been conducted using bibliometric methods. Braun et al. (1997) identified an exponential growth of pattern for publications in nano-science and technology starting in the early 1990s; Meyer and Persson (1998) characterized nanotechnology using bibliometric as well as patent data; Kostoff et al. (2006, 2007) reviewed the nanotechnology literature and analyzed its technical structure; Leydesdorff and Zhou delineated a core set of nanotechnology journals and a nanotechnology-relevant set (Leydesdorff and Zhou 2007; Zhou and Loet 2006); Porter and Youtie (2009) studied the extent and nature of interdisciplinary interchange in nanotechnology; Rafols and Meyer (2007, 2010) explored the extent and types of cross-disciplinary practices in nanotechnology; Huang et al. (2006) used a combination of basic bibliometric analysis and content visualization tools to identify growing nanotechnology trends; Guan and Ma (2007) provided an integrated bibliometric analysis of Chinese nanotechnology research community; and Bhattacharya et al. (2012) used bibliometric and innovation indicators to investigate to what extent China and India are able to assert their position in the global nanotechnology area.

Majority of studies on international collaboration in nanotechnology are based on papers, which are closer to scientific research. For example, Meyer and Persson (1998) revealed different patterns of international collaboration by co-authorship analysis: some countries tend to have bilateral relations with each other while others collaborate with a much larger array of nations. In order to examine the patterns of collaboration, Onel et al. (2011) built and analyzed a collaboration network of scientists and engineers who conduct research in nanotechnology, as well as established and studied the structure of information flow via citation network of papers authored by nano area scientists. Tang and Shapira (2011) combined bibliometric analysis and science mapping to examine the collaboration between China and the US in the field of nanotechnology. They found rapid increase in the number of China–US co-authored nanotechnology papers as well as structural changes in array of collaborative nanotechnology sub-fields. Wang et al. (2012) used bibliometric methods and social network analysis to study pattern of China–US scientific collaborations on individual level in the field of nanotechnology, showing that Chinese-American scientists have been playing an important role in China–US scientific collaboration. Ye et al. (2012) explored nanotechnology collaboration patterns and collaborators' performance through bibliometric and text mining analysis to draw policy implications to promote further research. Similar studies have also been conducted by Zhao and Guan (2011), Mehta et al. (2012) and Liu et al. (2012).

By contrast, patents reflect the latest technological inventions and encompass valuable information related to collaborative efforts. Patents provide a reliable quantization basis for technology collaboration studies (Zheng et al. 2012; Chen et al. 2013). As a result, some scholars began to study international collaboration of nanotechnology based on patent analysis. For example, Guan and Zhao (2012) investigated the impacts of university-industry technology collaboration on knowledge creation and patent value in the field of nanobiopharmaceuticals. The patent collaboration networks were examined with an aim to contribute to policy makers and relevant managers when making decisions for university, firm locality and choices on collaborators. In another studies, Guan and Shi (2012) constructed the patent citation networks at the patent document level and discovered the small world phenomenon, which is widely studied in co-authorship networks, but rarely touched in the citation networks.

Nanotechnology patents from 1991 to 2010 were retrieved and compiled in this study to provide an overview of nanotechnology development, as well as to reveal evolutionary trends and characteristics of international collaboration in nanotechnology. The history of the selected patents was first reviewed to investigate whether growing competitiveness in technology R&D is accompanied by intensification of international collaborations. The international collaboration of the top 20 countries/regions in international collaborative nanotechnology patents and their collaboration patterns were then discussed in a global context. Finally, comparison of citation impacts of international collaboration patents and total patents is discussed.

Methodology

The data

The USPTO is the federal agency responsible for granting patents and registering trademarks in the US. Founded in 1802, the USPTO has granted more than 4 million patents since 1976. Patents granted by the USPTO provide a relatively accurate picture of the world's technology distribution: Approximately half of the inventions of US patents are foreign-owned, and the numbers of US-granted invention patents in each country are roughly proportional to their country's gross domestic product. The patent data for this study were retrieved from the USPTO database and downloaded from the internet (http://www.uspto.gov) on May 29, 2012, which contain all US-granted patents with application years between 1991 and 2010.

Many attempts have been made to design the best search strategy for the identification of nanotechnology patents (Meyer 2000, 2001; Braun et al. 1997; Huang et al. 2004; Hullmann and Meyer 2003; Kostoff et al. 2006; Lee et al. 2006; Marinova and McAleer 2003; Porter et al. 2008; Schummer 2004). After reviewing a variety of such efforts, Wong et al. (2007) refined the keyword-search strategy of previous researchers together with the inclusion of an up-to-date set of Class 977 patents that have been reclassified by USPTO as nanotechnology. In this study, the co-authors performed similar search strategies as used by Wong et al. (see Appendix).

There are two methods to identify patents of a country in the USPTO database: by assignee country patents and by inventor country patents. Inventor country patents are more commonly used (i.e. the inventor country is the target that the patent will be attributed to) as registry of such patents reveal the inventive/innovative activity in one country. Thus, this study selects patents with co-inventors from more than one country to represent international collaboration patents.

Social network analysis

A social network represents a social structure of people, organizations, or countries that interact with one another. People, organizations and countries, commonly referred to as "actors", can be represented as nodes and their complex interrelations as edges. Social network analysis aims to detect and interpret the patterns of social ties among actors using statistics and visualization (Nooy et al. 2005).

Network analysis based on patent data has been widely used in international collaboration studies. For example, Fleming et al. (2007) developed a database on patent co-authorship to investigate the effects of collaboration networks on innovation. Chen and Guan (2010) investigated the impact of small world properties on innovation at national level with an empirical investigation of the patent collaboration networks from 16 main innovative countries during 1975–2006. Guan and Chen (2012) provided an empirical analysis of evolving knowledge networks of successful patent collaboration at national level.

In this study, the collaboration network was constructed using UCINET software, in which nodes represent the countries/regions and the edges among them represent the collaborations among countries/regions. The sizes of the nodes are determined by degree centrality (DC), which is a measure of the number of direct connections between nodes. The strength of the edges among nodes represents the quantity of collaboration. The more one countries collaborates with another, the darker the edges between them.

DC: The DC of a node in the network is based on the number of direct connections between that node and other nodes. Generally, the nodes with higher DC (which include more connections) are more central to the structure and generally have greater potential to influence other nodes. Cooperation networks are undirected. When an author is involved in cooperation, he or she is regarded as the "source" of information or as a "sink" or "receiver" of information. This is usually a measure of how influential (as "source") or prestigious (as "receiver") the node may be (Yin et al. 2006).

In order to explicitly reveal the development of DC for the countries/regions, the past 20 years from 1991 to 2010 were divided into three periods. Dynamic measures were added by dividing the change of DC for country i between the ($j + 1$)th period and the jth period by the average change of DC for all countries/regions over the past 20 years. If $\mathrm{DC}_{i,\,j}$ were the DC for country i in the jth period and set $\overline{\mathrm{DC}}$ as the average change of DC for all countries/regions over the past 20 years, then the development of DC for country i between the ($j + 1$)th period and the jth period ($\Delta\mathrm{DC}_{i,j}$) would be as follows,

$$\Delta\mathrm{DC}_{i,j} = \frac{\mathrm{DC}_{i,j+1} - \mathrm{DC}_{i,j}}{\overline{\mathrm{DC}}} \tag{1}$$

Density (D): The density is the proportion of collaboration in the network relative to the total number of possible collaboration ties. The higher the density is, the more closely the nodes in the network interact with each other. If the number of nodes in the network was g, and L set as the number of edges that actually exist between the neighboring nodes in the network, then the density of the overall network (D) would be the ratio of the number of edges that actually exist to the total number of possible edges between these neighboring nodes, as follows:

$$D = \frac{L}{C_2^g} = \frac{L}{g(g-1)\ /2} = \frac{2L}{g(g-1)} \tag{2}$$

In order to depict the development of network density more clearly, the past 20 years from 1991 to 2010 were divided into three periods. Dynamic measures were added by dividing the density change between the $(j+1)$th period and the jth period by the average density over the past 20 years. If D_j were the density in the jth period, then the development of density between the $(j+1)$th period and the jth period (ΔD_j) would be as follows,

$$\Delta D_j = \frac{D_{j+1} - D_j}{D} \tag{3}$$

Patent indicators

Citations per patent (CPP): CPP is the number of citations per patent within a certain period. CPP value is mainly used to measure the impact of each patent, and it displays the influence of patents on scientific and technical progress. CPP reflects patent quality and R&D level to some extent. When the number of patents increases rapidly, CPP are likely to be lower than the true long-term citation rates. This is because recent patents have not accumulated citations over any give citation window.

$$\mathrm{CPP} = \frac{\mathrm{NC}}{N} \tag{4}$$

NC: the sum of citations within a certain period, N: the total number of patents within the same period, CPP: the number of citations per patent within a certain period.

In order to describe the development of CPP values in detail, the past 20 years were divided into three periods. Dynamic measures were used by dividing the change of CPP values for country i between the $(j+1)$th period and the jth period by the average change of CPP values for all countries/regions over the past 20 years. If $\mathrm{CPP}_{i,j}$ was the CPP value for country i in the jth period, and set $\overline{\mathrm{CPP}}$ as the average change of CPP values for all countries/regions over the past 20 years, then the development of CPP value for country i between the $(j+1)$th period and the jth period ($\Delta\mathrm{CPP}_{i,j}$) would be as follows,

$$\Delta\mathrm{CPP}_{i,j} = \frac{\mathrm{CPP}_{i,j+1} - \mathrm{CPP}_{i,j}}{\overline{\mathrm{CPP}}} \tag{5}$$

Results and discussion

Overall growth trend

Owing much to emphasis placed on nanotechnology R&D expenditure and the demand for S&T innovation, the world has witnessed spectacular growth in nanotechnology innovations in recent years. Nanotechnology patents have shown an increase as an important output indicator. The total number of nanotechnology patents over the past 20 years is 17,899, which has exhibited continuous growth from 1990 to 2006, as illustrated in Fig. 1. Since 2006, the number of patents has gradually declined. The time lag between the application year and patent approval year may have been one factor that results the apparent decline in the number of patents since 2006, as data were collected and analyzed based on patent application year. International collaboration nanotechnology patents across the world has likewise showed continued growth until 2006, with the number increasing from 5 in 1991 to 163 in 2006. The time lag between patent application year and patent approval may also be the factor that results the decline of international collaboration patents after 2006 on the database.

Figure 2 highlights the share of international collaboration patents in the total number of patents. From 1991 to 1997, the share showed an increasing trend, with the highest point of 9.1 % in 1995. From 1998 to 2001, the share maintained a relatively high level, above 9.7 %. Although there was a drop of 3 % in 2002, the share rose again in the following 8 years. In short, despite slight fluctuations, the share of international collaboration patents exhibited an overall upward trend, increasing from less than 5 % in 1991 to more than 9 % in 2010. This growth indicates that international collaboration plays an increasing important role in nanotechnology innovation. In order to study the evolution, the co-authors divided the past 20 years into three periods: an initial stage of 7 years, a mid stage of 6 years, and a late stage of 7 years.

Key players

The top 20 countries/regions in international collaboration nanotechnology patents from 1991 to 2010 are listed in Table 1. The USA took the leading position, accounting for over one-third of the international collaboration nanotechnology patents in the world. Though the percentage of the international collaboration patents over total number of patents remain relatively low (10.4 %), international collaboration nanotechnology patents in the USA maintained highest in the world, due to its large number of total nanotechnology patents. Similar to the USA, Japan, South Korea and Taiwan, with share lower than 15 %, have nevertheless maintained high numbers of international collaboration nanotechnology patents.

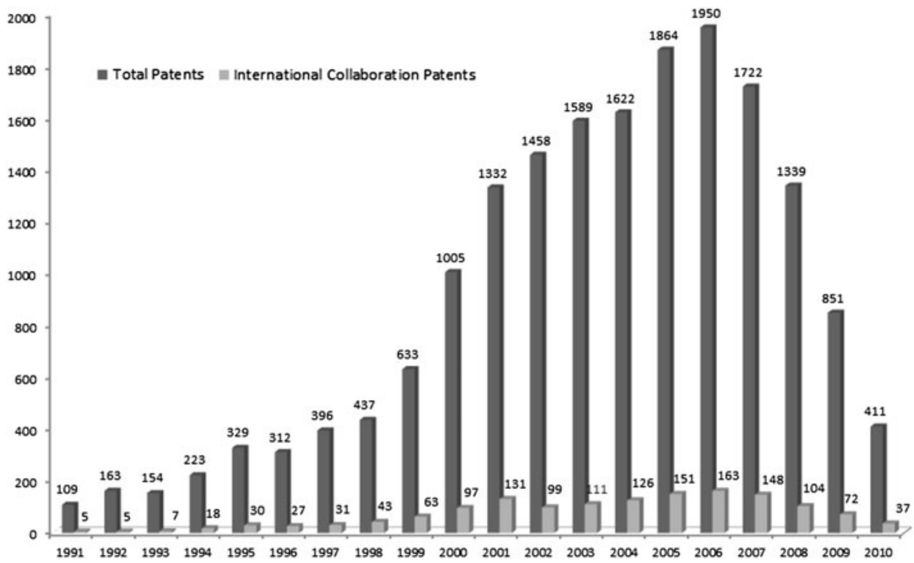

Fig. 1 The number of total patents and international collaboration patents in nanotechnology by year

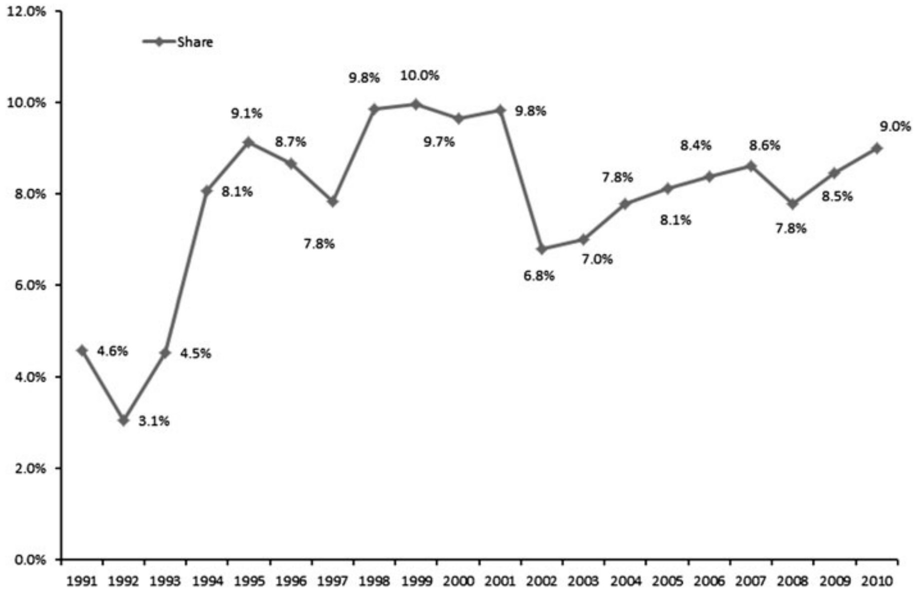

Fig. 2 The share of international collaboration patents in total patents by year

Countries/regions such as Switzerland, the UK, the Netherlands, Belgium, Sweden, Russia, India and Singapore show much higher percentage in their proportion of international collaboration nanotechnology patents, all above 40 %. Switzerland, with 63.5 % of international collaboration nanotechnology patents, has the highest rate of all countries. These countries/regions served as important actors in international collaboration of nanotechnology development, though the numbers of domestic nanotechnology patents remain relatively low. Other countries/regions in the rankings are Germany, France, Canada, China, Israel, Australia and Italy. Whether from the perspective of the number of total nanotechnology patents or from the perspective of the share of international collaboration nanotechnology patents, these countries were in an intermediate level.

Table 2 shows the shares of international collaboration nanotechnology patents in the total number of nanotechnology patents for the top 20 countries/regions in three periods. Most of the top 20 countries/regions, including the USA, Germany, Japan, France, Switzerland, South Korea, the Netherlands, Belgium, Israel, India, Singapore and Italy, show increased international collaboration over the past decade. Although the share of international collaboration nanotechnology patents in the USA has maintained low, the share of international collaborations continued to grow up in the past 20 years. Japan and South Korea show similar signs. European countries such as Switzerland, the Netherlands and Belgium have already reached high level of international collaboration nanotechnology before the year of 2003, but still continued to rise from 2004 to 2010.

The shares of global international collaboration nanotechnology patents by the top 20 countries/regions during the three periods are shown in Table 3. The USA has led the chart for the past 20 years, and its share continually climbed, increasing from 20.7 to 36.0 %. This asserts the USA's dominance in nanotechnology development worldwide and a more important role the USA has played in the international collaboration of nanotechnology,

Table 1 Top 20 countries/regions owning international collaboration nanotechnology patents in the world

Country (regions)	Nanotechnology patents (A) Rank (number)	ICNPs (B) Rank (number)	B/A Rank (share)	B/(ICNPs in the world) Rank (share)
USA	1 (11,186)	1 (1158)	18 (10.4 %)	1 (35.9 %)
Germany	4 (854)	2 (290)	12 (34.0 %)	2 (9.0 %)
Japan	2 (2,283)	3 (181)	19 (7.9 %)	3 (5.6 %)
Canada	7 (445)	4 (160)	10 (36.0 %)	4 (5.0 %)
UK	9 (316)	5 (148)	7 (46.8 %)	5 (4.6 %)
France	6 (478)	6 (135)	15 (28.2 %)	6 (4.2 %)
Switzerland	10 (203)	7 (129)	1 (63.5 %)	7 (4.0 %)
China	8 (388)	8 (106)	16 (27.3 %)	8 (3.3 %)
Taiwan	5 (670)	9 (95)	17 (14.2 %)	9 (2.9 %)
South Korea	3 (1,209)	10 (92)	20 (7.6 %)	9 (2.9 %)
Netherlands	14 (120)	11 (68)	3 (56.7 %)	11 (2.1 %)
Belgium	15 (110)	12 (62)	4 (56.4 %)	12 (1.9 %)
Sweden	12 (135)	13 (54)	9 (40.0 %)	13 (1.7 %)
Israel	11 (151)	14 (49)	13 (32.5 %)	14 (1.5 %)
India	17 (89)	14 (49)	5 (55.1 %)	14 (1.5 %)
Russia	19 (77)	16 (45)	2 (58.4 %)	16 (1.4 %)
Singapore	18 (80)	17 (37)	8 (46.3 %)	17 (1.1 %)
Australia	16 (105)	18 (36)	11 (34.3 %)	17 (1.1 %)
Italy	13 (125)	18 (36)	14 (28.8 %)	17 (1.1 %)
Spain	20 (54)	20 (29)	6 (53.7 %)	20 (0.9 %)

Data compiled by authors for this study

ICNPs international collaboration nanotechnology patents

which is due to the rapid growth in the number of total nanotechnology patents, as well as the growth in the share of international collaboration as shown in Table 2.

Besides the USA, Asian countries/regions also exhibited strong momentum of development, particularly Japan, South Korea, China, India and Taiwan. South Korea showed outstanding results, with its share of global international collaboration nanotechnology patents increasing from zero to 4.3 %.The growing proportions of Asian countries also resulted in the rapid growth in the number of total patents and the share of international collaboration during the recent years as shown in Table 2.

By contrast, the share owned by some European countries show decline as described in Table 3. For instance, though Germany maintained second place throughout the period, the share it held gradually decreased from 12.2 to that of 7.4 %. Germany may be replaced by Japan in the near future if situation remains unchanged. Likewise, Switzerland’s share of international collaboration nanotechnology patents dropped sharply, lowering from 12.2 to 3.5 %, as shown in Table 3. Detailed studies in Table 2 have revealed that the share of international collaboration nanotechnology patents out of total nanotechnology patents in Switzerland maintained a very high level and kept increasing during the past 20 years. Thus, the obvious decline in Switzerland mentioned above was due to the slow growth in the number of its total nanotechnology patents. Similar situations also occurred in the UK, France, Sweden and Spain. As for the other countries, there was no significant change during the past 20 years.

Table 2 The total nanotechnology patents, the international collaboration nanotechnology patents and the shares of international collaboration nanotechnology patents for the top 20 countries/regions in the three periods

Country (regions)	1991–1997 Patents (ICNPs, share)	1998–2003 Patents (ICNPs, share)	2004–2010 Patents (ICNPs, share)
USA	1,015 (17, 1.67 %)	4,153 (348, 8.38 %)	6,018 (609, 10.12 %)
Germany	86 (10, 11.63 %)	400 (127, 31.75 %)	368 (126, 34.24 %)
Japan	430 (2, 0.47 %)	789 (53, 6.72 %)	1,064 (96, 9.02 %)
Canada	33 (2, 6.06 %)	189 (66, 34.92 %)	223 (77, 34.53 %)
UK	46 (8, 17.39 %)	162 (75, 46.30 %)	108 (47, 43.52 %)
France	61 (9, 14.75 %)	197 (52, 26.40 %)	220 (65, 29.55 %)
Switzerland	27 (10, 37.04 %)	85 (46, 54.12 %)	91 (60, 65.93 %)
China	5 (1, 20.00 %)	65 (23, 35.38 %)	318 (76, 23.90 %)
Taiwan	8 (1, 12.50 %)	158 (14, 8.86 %)	504 (78, 15.48 %)
South Korea	10 (0, 0)	259 (14, 5.41 %)	940 (73, 7.77 %)
Netherlands	9 (1, 11.11 %)	47 (21, 44.68 %)	64 (22, 50.00 %)
Belgium	5 (0, 0)	44 (22, 50.00 %)	61 (36, 59.02 %)
Sweden	11 (4, 36.36 %)	59 (25, 42.37 %)	65 (23, 35.38 %)
Israel	17 (1, 5.88 %)	69 (20, 28.99 %)	65 (19, 29.23 %)
India	1 (0, 0)	32 (11, 34.38 %)	56 (37, 66.07 %)
Russia	1 (0, 0)	38 (26, 68.42 %)	38 (19, 50.00 %)
Singapore	0 (0, –)	31 (13, 41.94 %)	49 (22, 44.90 %)
Australia	8 (2, 25.00 %)	38 (7, 18.42 %)	59 (24, 40.68 %)
Italy	4 (0, 0)	53 (15, 28.30 %)	68 (20, 29.41 %)
Spain	7 (3, 42.68 %)	15 (4, 26.67 %)	32 (22, 68.75 %)

Data compiled by authors for this study

ICNPs international collaboration nanotechnology patents

Collaboration patterns

Figure 3 displays the collaboration network of the top 20 countries/regions from 1991 to 2010. USA is shown in Fig. 3 with the highest value of DC, while, Germany, Japan, the UK, China, South Korea, Canada, France and India come next, having all belonged to the first tier of the collaboration network for the past 20 years. This indicates that these countries have exerted great influence on global nanotechnology collaborations. Additionally, the USA has developed close collaborative relationships with several countries/regions, including Germany, Japan, Canada, the UK, South Korea, China and Taiwan.

Observing the ties among the top 20 countries, different patterns of collaborations can also be distinguished. Some countries/regions collaborate with a wide range of countries/regions, while others are more selective with their collaborative partners. For instance, the USA cooperated with every country noted in the collaboration network. Germany, the UK and Japan came quite close to same range of collaboration. However, Spain, Israel, Russia, Singapore and Taiwan collaborate internationally in a smaller scale. For example, Taiwan may have had experience collaborating with USA, China, India, Japan, Russia and Singapore, yet it has only maintained long-term collaborative relationship with USA and China. Similarly, China's international collaboration partners were relatively narrow when China compares its collaboration range with the USA and other western countries. China

Table 3 The shares of the top 20 countries/regions that held in international collaboration patents of the world during the three periods

Country (regions)	1991–1997 Rank (share)	1998–2003 Rank (share)	2004–2010 Rank (share)
USA	1 (20.7 %)	1 (32.4 %)	1 (36.0 %)
Germany	2 (12.2 %)	2 (11.8 %)	2 (7.4 %)
Japan	8 (2.4 %)	5 (4.9 %)	3 (5.7 %)
Canada	8 (2.4 %)	4 (6.1 %)	4 (4.6 %)
UK	5 (9.8 %)	3 (7.0 %)	10 (2.8 %)
France	4 (11.0 %)	6 (4.8 %)	8 (3.8 %)
Switzerland	2 (12.2 %)	7 (4.3 %)	9 (3.5 %)
China	11 (1.2 %)	10 (2.1 %)	6 (4.5 %)
Taiwan	11 (1.2 %)	15 (1.3 %)	4 (4.6 %)
South Korea	15 (0.0 %)	15 (1.3 %)	7 (4.3 %)
Netherlands	11 (1.2 %)	11 (2.0 %)	13 (1.9 %)
Belgium	15 (0.0 %)	11 (2.0 %)	12 (2.1 %)
Sweden	6 (4.9 %)	9 (2.3 %)	14 (1.4 %)
Israel	11 (1.2 %)	13 (1.9 %)	19 (1.1 %)
India	15 (0.0 %)	18 (1.0 %)	11 (2.2 %)
Russia	15 (0.0 %)	8 (2.4 %)	19 (1.1 %)
Singapore	15 (0.0 %)	17 (1.2 %)	16 (1.3 %)
Australia	8 (2.4 %)	19 (0.7 %)	14 (1.4 %)
Italy	15 (0.0 %)	14 (1.4 %)	18 (1.2 %)
Spain	7 (3.7 %)	20 (0.4 %)	16 (1.3 %)

Data compiled by authors for this study

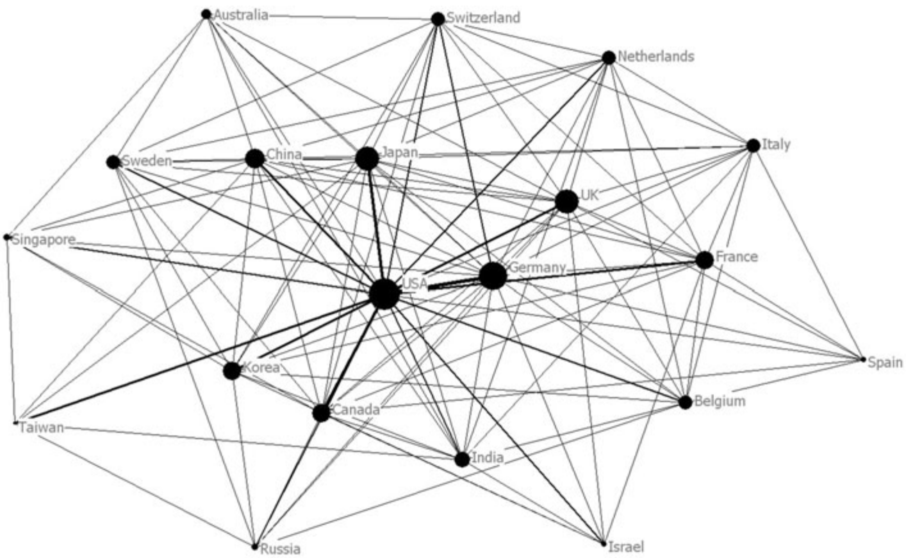

Fig. 3 The collaboration network of the top 20 countries/regions from 1991 to 2010

and Taiwan, though illustrating significant progress in total number of nanotechnology patents, are advised to expand its international collaboration range in order to promote development. Previous studies based on publications also reveal two patterns of collaborations, but the same country may adopt different collaboration pattern in the publication area. For example, Japan, cooperated with a wide range of countries in patenting activities, but only selectively cooperated with some leading countries in publications (Meyer and Persson 1998).

The collaboration networks of the top 20 countries/regions in the three periods are displayed in Figs. 4, 5 and 6 respectively. The number of countries/regions participating in international collaboration continued to increase from 1991 to 2010; From 1991 to 1997, there were only 13 countries/regions in the collaboration network; From 1998 to 2003, the number of the included countries/regions expanded to 19; in the period of 2004 to 2010, all the top 20 countries/regions were involved in the cooperation network. The density of the overall network also continued to rise, as revealed in Table 4, indicating increasingly close collaborations between countries/regions, which can be reflected from the increasingly dense ties among the nodes in Figs. 4, 5 and 6. In order to depict the development of network density more clearly, we compare the development of network density between the three periods. As shown in Table 5, the developments of density between different periods were 40 and 29 %, respectively. Though international collaboration among countries has strengthened as seen in Table 4, the growth trend has somewhat slowed down.

As shown in Figs. 4, 5 and 6, the USA has remained in first place in the collaboration network throughout the past 20 years. The DC of the USA was much higher than that of the other countries/regions as depicted in Table 6, showing USA's dominance in nanotechnology collaboration network. From 1991 to 1997, the UK exhibited relatively a higher DC alongside the USA. From 1998 to 2003, apart from the USA and the UK, there were three new countries with high DC that came into sight: Germany, France and Japan. Likewise, from 2004 to 2010, China, South Korea and Canada began to show high DC. As

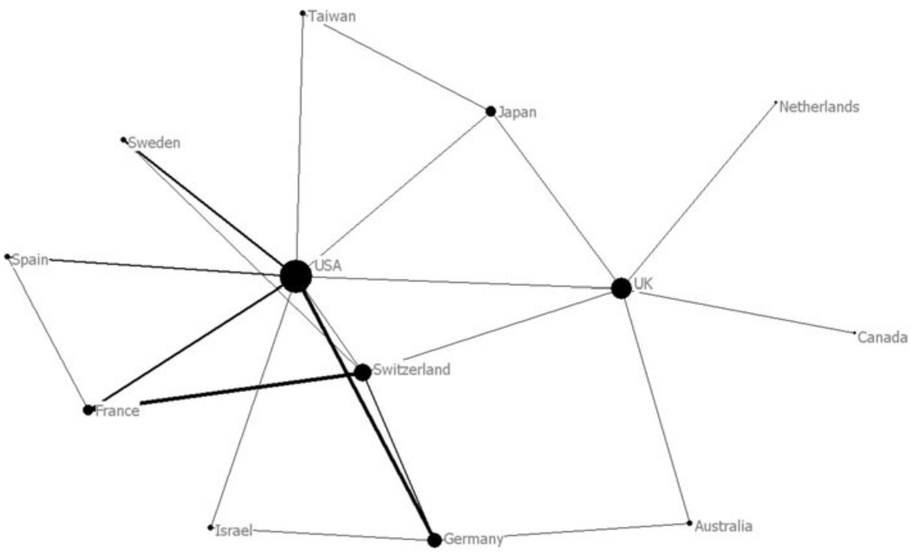

Fig. 4 The collaboration network of the top 20 countries/regions from 1991 to 1997

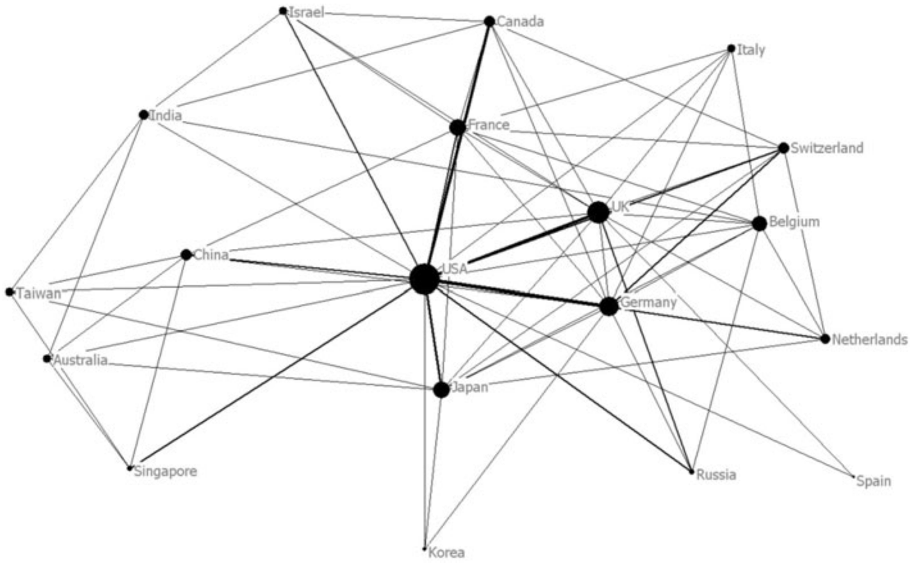

Fig. 5 The collaboration network of the top 20 countries/regions from 1998 to 2003

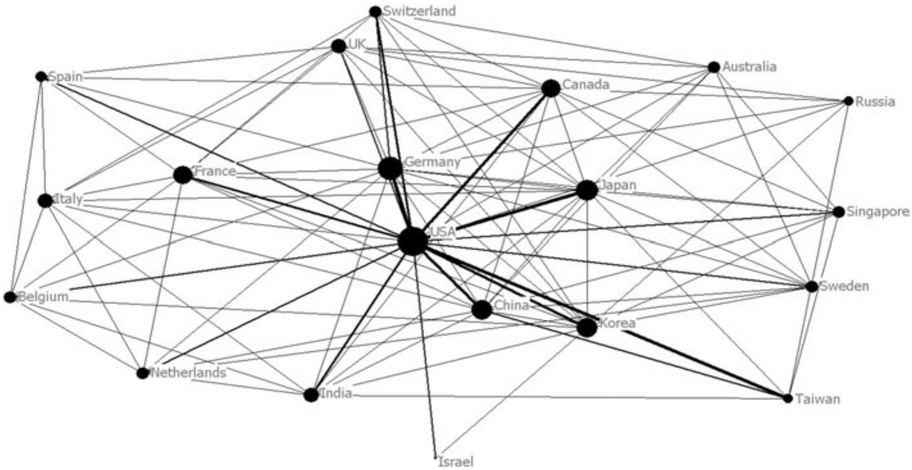

Fig. 6 The collaboration network of the top 20 countries/regions from 2004 to 2010

Table 4 The density of the collaboration network in three periods

	1991–1997	1998–2003	2004–2010	1991–2010
Density	0.23	0.40	0.52	0.42

Data compiled by authors for this study

shown in Table 6, most of the top 20 countries/regions have show an increase in DC, such as Germany, Canada, France, the Netherlands, Russia, Australia, Italy, Japan, China, Taiwan, South Korea, India and Singapore. Still, few countries/regions have exhibited a

Table 5 The development of network density in three periods

	From (1991–1997) to (1998–2003)	From (1998–2003) to (2004–2010)
The development of density	40 %	29 %

Data compiled by authors for this study

Table 6 The degree centrality of top 20 countries/regions in the three periods

Country (regions)	1991–1997	1998–2003	2004–2010	1991–2010
USA	75.00	100.00	100.00	82.61
Germany	33.33	66.67	84.21	78.26
Japan	25.00	55.56	73.68	69.57
Canada	8.33	38.89	63.16	56.52
UK	50.00	72.22	52.63	69.57
France	25.00	55.56	63.16	56.52
Switzerland	41.67	38.89	42.11	47.83
China	–	38.89	68.42	60.87
Taiwan	16.67	27.78	31.58	26.09
South Korea	–	16.67	68.42	56.52
Netherlands	8.33	33.33	42.11	47.83
Belgium	–	50.00	42.11	47.83
Sweden	16.67	–	42.11	47.83
Israel	16.67	27.78	10.53	30.44
India	–	33.33	52.63	52.17
Russia	–	22.22	31.58	34.78
Singapore	–	22.22	42.11	34.78
Australia	16.67	27.78	42.11	39.13
Italy	–	27.78	52.63	47.83
Spain	16.67	11.11	36.84	30.44
Average	26.92	40.35	52.11	50.87

Data compiled by authors for this study

significant decrease in DC. Detailed studies in Table 7 explicitly reveal the development of DC for top 20 countries/regions. It can be seen that though there were continual increases in the development of DC for Germany, Japan, Canada, France, Taiwan and Netherlands, the development were obviously becoming slower from the second period to the third period. Additionally, the development in the UK, Belgium and Israel were negative from the second period to the third period. There has shown lower influence of these countries in international collaboration as the DC for the three countries decreased.

Citation impact

Table 8 compares the average citation rates of total nanotechnology patents and international collaboration nanotechnology patents during the three periods. From 1991 to 1997, there were 1,686 nanotechnology patents worldwide, receiving 1,889 citations. The average citation rate reached 1.12, much higher than that of international collaboration nanotechnology patents during the same period, which remained only 0.35. The CPP

Table 7 The development of degree centrality for top 20 countries/regions in the three periods

Country (regions)	From (1991–1997) to (1998–2003)	From (1998–2003) to (2004–2010)
USA	1.86	0.00
Germany	2.48	1.49
Japan	2.28	1.54
Canada	2.28	2.06
UK	1.65	−1.67
France	2.28	0.65
Switzerland	−0.21	0.27
China	–	2.51
Taiwan	0.83	0.32
South Korea	–	4.40
Netherlands	1.86	0.75
Belgium	–	−0.67
Sweden	–	–
Israel	0.83	−1.47
India	–	1.64
Russia	–	0.80
Singapore	–	1.69
Australia	0.83	1.22
Italy	–	2.11
Spain	−0.41	2.19

Data compiled by authors for this study

Table 8 The citation per patents (CPP) of total nanotechnology patents and international collaboration nanotechnology patents in the world during the three periods

	Total nanotechnology patents			International collaboration nanotechnology patents		
	Patents	Citations	CPP	Patents	Citations	CPP
1991–1997	1,686	1,889	1.12	37	13	0.35
1998–2003	6,454	2,168	0.34	505	96	0.19
2004–2010	9,759	4,701	0.48	801	336	0.42

Data compiled by authors for this study

values of international collaboration nanotechnology patents were lower than those of the total nanotechnology patents for the second and third stage. This indicates that, from a global perspective, the international collaboration has not exerted a raising effect on the citation impact of nanotechnology patents during the past 20 years. Nevertheless, it is also worth mentioning that the gap between international collaboration nanotechnology patents and total nanotechnology patents in terms of citation impacts had become narrower: the gap from 1991 to 1997 was 0.77; 0.15 from 1998 to 2003, and 0.06 from 2004 to 2010. Consequently, the CPP values of international collaboration nanotechnology patents will probably catch up with and exceed the CPP values of total nanotechnology patents in the near future. International collaboration may soon play a more active role in enhancing citation impacts of nanotechnology patents.

Table 9 presents the average citation rates of total nanotechnology patents and international collaboration nanotechnology patents of the top 20 countries/regions during the three periods. Throughout the past 20 years, the CPP values of international nanotechnology patents were distinctively lower than those of the total nanotechnology patents in the USA and Canada, which was consistent with the global situation as mentioned above. Though the number of international collaboration nanotechnology patents has increased significantly in the past 20 years as seen in Table 2, such patents have not asserted an active role in enhancing the citation impacts of nanotechnology patents of USA and Canada. As for Germany and Switzerland, before the year of 1998, the number of international collaboration nanotechnology patents were quite low, only 10 for each of them, but they played an active role in raising citation impacts of nanotechnology patents. However, from 1998 to 2010, the CPP values of international collaboration patents became lower than those of the total patents, which indicate that international collaboration does not always pay off in nanotechnology innovation for Germany and Switzerland. The quality of international collaboration patents does not get enhanced with the increase of the quantity of those patents in Germany and Switzerland.

The four countries above aside, the CPP values of international collaboration nanotechnology patents were higher than that of the total nanotechnology patents from 2004 to 2010. This indicates that though international collaboration in the field of nanotechnology

Table 9 The citation per patents (CPP) of total nanotechnology patents and international collaboration nanotechnology patents in top 20 countries/regions during the three periods

	1991–1997		1998–2003		2004–2010	
	Total patents	ICNPs	Total patents	ICNPs	Total patents	ICNPs
USA	1.10	0.35	0.34	0.16	0.63	0.48
Germany	0.40	0.60	0.26	0.20	0.37	0.37
Japan	1.64	0.00	0.42	0.19	0.30	0.37
Canada	0.76	0.00	0.49	0.19	0.35	0.31
UK	0.30	0.00	0.39	0.11	0.15	0.49
France	0.31	0.78	0.17	0.08	0.15	0.38
Switzerland	0.41	0.60	0.61	0.46	0.12	0.10
China	0.00	0.00	0.15	0.04	0.18	0.29
Taiwan	0.00	0.00	0.36	0.36	0.27	0.38
South Korea	0.00	–	0.35	0.29	0.24	0.33
Netherlands	0.67	0.00	0.17	0.38	0.34	0.56
Belgium	0.20	–	0.36	0.14	0.30	0.47
Sweden	0.18	0.00	0.07	0.00	0.26	0.35
Israel	0.35	0.00	0.32	0.05	0.77	1.47
India	0.00	–	0.00	0.00	0.57	0.81
Russia	0.00	–	0.32	0.27	0.24	0.42
Singapore	–	–	0.32	0.38	0.39	0.59
Australia	0.00	0.00	0.42	0.71	0.20	0.25
Italy	0.25	–	0.09	0.20	0.21	0.25
Spain	0.00	0.00	1.80	0.00	0.22	0.32

ICNPs international collaboration nanotechnology patents

Data compiled by authors for this study

has not yet been found globally significant in terms of citation impacts as mentioned above, it has already played an incremental position in improving the citation impacts of nanotechnology patents for most of the top 20 countries/regions since 2004. As shown in Table 2, most of the top 20 countries/regions had no more than 100 international collaboration nanotechnology patents. This shows that international collaboration is important for improving the citation impacts of nanotechnology patents for most countries/regions, although the number of them is rather low. Additionally, the narrowing gap between global international collaboration patents and total patents from 2004 to 2010 as described in Table 8, is a result of increase in CCP values of international collaboration nanotechnology patents in most of the top 20 countries in Table 9.

In order to describe the development of CPP values in detail, we compared the development of CPP values between different periods, as shown in Table 10. To compare the differences, the change of CPP values of total patents and international collaboration patents for one country/region were both divided by the average change of CPP values of total patents for all countries/regions. Since the average CPP values of total nanotechnology patents from 2004 to 2010 were lower than those from 1991 to 1997, the corresponding average citation rates improved when the development of CPP value in Table 10 were negative. The more negative the development of CPP values are, the faster the growing rates for CPP values become. As a result, the growth rates for CPP values for international

Table 10 The development of citation per patents (CPP) of total nanotechnology patents and international collaboration nanotechnology patents in top 20 countries/regions during the three periods

	Total nanotechnology patents		International collaboration nanotechnology patents	
	From (1991–1997) to (1998–2003)	From (1998–2003) to (2004–2010)	From (1991–1997) to (1998–2003)	From (1998–2003) to (2004–2010)
USA	0.97	2.07	1.19	1.39
Germany	0.18	0.79	2.50	0.74
Japan	1.56	−0.86	−1.19	0.78
Canada	0.35	−1.00	−1.19	0.52
UK	−0.12	−1.71	−0.69	1.65
France	0.18	−0.14	4.38	1.30
Switzerland	−0.26	−3.50	0.88	−1.57
China	−0.19	0.21	−0.25	1.09
Taiwan	−0.46	−0.64	−2.25	0.09
South Korea	−0.45	−0.79	–	0.17
Netherlands	0.64	1.21	−2.38	0.78
Belgium	−0.21	−0.43	–	1.43
Sweden	0.14	1.36	0.00	1.52
Israel	0.04	3.21	−0.31	6.17
India	0.00	4.07	–	3.52
Russia	−0.41	−0.57	–	0.65
Singapore	–	0.50	–	0.91
Australia	−0.54	−1.57	−4.44	−2.00
Italy	0.21	0.86	–	0.22
Spain	−2.31	−11.29	0.00	1.39

Data compiled by authors for this study

collaboration patents have always been faster than the total patents in a few countries all through the past 20 years, such as Japan, UK, Israel, Netherlands, Sweden and Canada. In these countries, international collaboration probably play an active role in enhancing the citation rates for patents right now or in future. Although in Canada, the CPP values of international nanotechnology patents remain lower than those of the total nanotechnology patents throughout the past 20 years, this situation will change if the growing rate for international collaboration patents maintain faster than that for the total patents.

Conclusions

The collaborative technological information in patent documents provides useful tools to the studies of international collaboration development of nanotechnology. Following conclusions are drawn from the analysis of international collaboration nanotechnology patents from 1991 to 2010.

Owing to the rapid development and ardent enthusiasm for nanotechnology globally, internationally collaborated nanotechnology patents have shown a steady growth; the proportion of internationally collaborated patents also exhibits an overall upward trend.

Since the early 1990s, the world has witnessed spectacular growth in nanotechnology innovation. As the number of total nanotechnology patents increased, international collaboration patents also exhibited rapid growth globally during the past 20 years.

Likewise, the proportion of international collaboration nanotechnology patents in the total nanotechnology patents has also increased from that of less than 5 % in 1991 to more than 9 % in 2010. This shows that international collaboration has played an important role fostering global nanotechnology innovation.

The USA has become the most important player in international collaboration nanotechnology patents, while the growth is also evident in Asian countries/regions such as Japan, South Korea, China, India and Taiwan. European influence has declined over the years in its number of international collaboration nanotechnology patents.

The USA took the leading position in international collaboration nanotechnology patents with largest number of nanotechnology patents worldwide. The USA will continue to assert influence on development of international collaboration nanotechnology patents due to its increasing number of total nanotechnology patents and increasing share of international collaboration nanotechnology patents.

Asian countries/regions, such as Japan, South Korea, China, India and Taiwan, played considerately important roles in international collaboration nanotechnology patents. Similar to the USA, Asian countries/regions exhibited strong momentum of development, resulting from the rapid growth both in the number of total nanotechnology patents and in the share of international collaboration nanotechnology patents.

European countries, such as Germany, Switzerland, the UK, Sweden and Spain, once played a vital role in global international collaboration nanotechnology patents due to the very high share of international collaboration nanotechnology patents in total nanotechnology patents. However, the importance of these countries is weakening due to their relatively slower growth in the number of total nanotechnology patents.

Among countries that have become increasingly involved in international collaboration development of nanotechnology, some countries active seek international collaboration while others may be more selective in choosing their collaborative partners.

During the past 20 years, more and more countries have become involved in international collaboration of nanotechnology as time goes by. Meanwhile, the continually rising density of the collaboration network evidently shows that the cooperation among countries/regions has been increasingly closer.

There are two collaboration patterns for countries/regions to engage in collaboration in nanotechnology: (1) countries/regions that collaborate with a wide range of countries, such as the USA, Germany, the UK and Japan; (2) countries/regions that selectively collaborate with only a few other countries, such as Spain, Israel, Russia, Singapore and Taiwan.

The values of DC reveal that the USA and the UK have belonged to the first tier of international collaboration in nanotechnology development throughout the past 20 years. Meanwhile, Germany, France, Japan, Canada, China and South Korea have exerted greater influence steadily.

International collaboration has yet to be found globally significant in terms of patent citation impact, however it has become incremental in improving citation impacts in most of the top 20 countries since 2004.

In the past 20 years, international collaboration has not exerted raising effect on the citation impact of nanotechnology patents globally. The CPP values of international collaboration nanotechnology patents were lower than those of total nanotechnology patents. However, international collaboration may play a more active role in enhancing the citation impact of nanotechnology patents in the future as the gap between the CPP values of international collaboration nanotechnology patents and that of total nanotechnology patents is narrowing.

Except for the USA, Canada, Germany and Switzerland, studies reveal that the CPP values of international collaboration nanotechnology patents were higher than those of the total nanotechnology patents from 2004 to 2010 in top 20 countries/regions. Though international collaboration has not yet found globally significant in terms of citation impacts, it has become instrumental in improving the citation impacts of nanotechnology patents for most of the top 20 countries/regions since 2004.

The international collaboration development of nanotechnology has been explored through patent network analysis in this study, aiming to provide an objective statistical reference for future policy-making and academic research. Detailed studies of social network analysis, such as small world phenomena and K-core analysis will be able to provide more useful information. Such research may help governments find influential partners in order to utilize resources worldwide and compete in the R&D of nanotechnology globally. These suggestions can serve as good topics for future studies.

Appendix

Search strategy for nanotechnology patents

((CCL/977/$ OR ABST/((((((((((((((((((((((Nano$ OR “Self assemble”) OR “Self assembly”) OR “Self-assembl$”) OR “Atomic force microscope”) OR “Atomic force microscopy”) OR “Atomic-force-microscop$”) OR “Scanning tunneling microscope”) OR “Scanning tunneling microscopy”) OR “Scanning-tunneling-microscop$”) OR “Atomistic simulation”) OR Biomotor) OR “Molecular device”) OR “Molecular electronics”) OR “Molecular modeling”) OR “Molecular motor”) OR “Molecular sensor”) OR “Molecular simulation”) OR “Quantum computing”) OR “Quantum dot”) OR “Quantum dots”) OR “Quantum effect”) OR “Quantum effects”)) AND APD/19910101->20101231)

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