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Nanotechnology strength indicators: international rankings based on US patents

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Abstract
Technological strength indicators (TSIs) based on patent statistics for 1975–2000 are used to analyse patenting of nanotechnology in the USA, and to compile international rankings for the top 12 foreign patenting countries (namely Australia, Canada, France, Germany, Great Britain, Italy, Japan, Korea, the Netherlands, Sweden, Switzerland and Taiwan). As the indicators are not directly observable, various proxy variables are used, namely the technological specialization index for national priorities, patent shares for international presence, citation rate for the contribution of patents to knowledge development and rate of assigned patents for potential commercial benefits. The best performing country is France, followed by Japan and Canada. It is shown that expertise and strength in nanotechnology are not evenly distributed among the technologically advanced countries, with the TSIs revealing different emphases in the development of nanotechnology.

1. Introduction

Q.1 A prominent feature of the 21st century is the upsurge of interest in the creation, dissemination and application of knowledge. The transition to a knowledge-based society and a learning economy leads to a new set of economic activities, structures and relationships. This 'new' economy is based on the all-pervasive new technologies, such as information technologies, which make all sectors knowledge intensive. These changes are already evident in a shift from the manufacturing to the services sector, upskilling of the workforce with an increase in white-collar jobs, increasing exports of high technology products, and significant investment in R&D, innovation and information, and communication technologies (Lundvall 1999, Organisation for Economic Cooperation and Development (OECD) 1996, 1999).

The importance of these new knowledge-intensive technologies is widely recognized and has been growing consistently. There are, however, other clusters of technologies which are presently in their infancy, but which are expected to have a significant impact in the future. The focus of this paper is on a specific member of this class of technologies, namely nanotechnology. According to Compañó and Hullmann (2002), the progress of nanotechnology in the last few decades has made it one of the key enabling technologies of the new century.

Since 1421, when the State of Venice gave a monopoly to Phillipo Brunillesci to use his invention of a floating architectural crane (Hall 1997), the patent system has become a firmly entrenched mechanism in market economies. Patent law has existed in the USA for more than 200 years, with the first such law having been passed by Congress in 1790. From the 1980s onward, there was been a large increase in the number of applications and granted patents (Patel and Pavitt 1995, Arundel and Kabla 1998, Kortum and Lerner 1999). This surge in patenting activities reflects the beliefs of industrialists, economists, politicians and lawyers, among others, that patents are conductive to economic and social progress. Despite periodic criticisms, there has been a general tendency to reaffirm and even expand the patent system (Arup 1993). A number of studies have also confirmed that patenting activities cause subsequent and immediate market changes (Soete 1987, Griliches *et al* 1991, Ernst 1995, 1997), such as the penetration

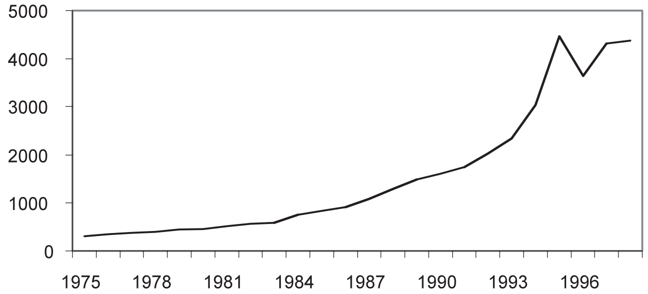

Figure 1. Annual US nanotechnology patents by year of application, 1975–98. (Note: the data were extracted on 5 March 2002.)

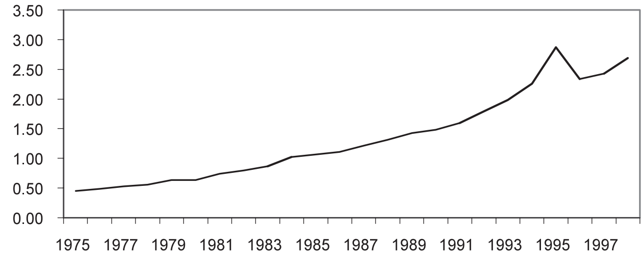

Figure 2. Annual share of US nanotechnology patents to total US patents by year of application, 1975–98. (Note: the data were extracted on 5 March 2002.)

of Japanese electronic products on the foreign markets or the world dominance of multinational pharmaceutical companies.

The US economy is particularly attractive to innovators and entrepreneurs because of its large size and technologically advanced nature. Consequently, the US Patent and Trademark Office (PTO) receives by far the largest number of foreign applications (Archibugi 1992), with close to 50% of all patents in the USA being granted to foreigners (Griliches 1990). The US government has also adopted nanomaterials as a priority funding and research area through its national nanotechnology initiative. If a country aspires to be a leader in the development of these technologies, its intellectual property rights must be protected and its presence in the US market will need to be significant.

This paper analyses innovation in nanotechnology in the USA, based on patent data for the period 1975–2000. An analysis of general trends in nanotechnology patents in section 2 is followed by a discussion of technological strength indicators (TSIs) based on patent statistics in section 3. The TSIs are used to assess the current national status and nanotechnological advantages for the top 12 foreign patenting countries in the USA (namely Australia, Canada, France, Germany, Great Britain, Italy, Japan, the Netherlands, South Korea, Sweden, Switzerland and Taiwan), and to provide international nanotechnology rankings in section 4. Some concluding remarks are given in section 5.

2. Nanotechnology patents in the USA

According to Crandall (1996), nanotechnology will soon create effective machines and molecular motors as small as DNA. This capacity to manipulate matter at the level of atoms and molecules with extremely high precision is expected to change the economic, ecological and cultural fabric of society dramatically. Foresight experts saw the beginning of the nanotechnology revolution in the late 1980s (Crandall and Lewis 1992). In addition to their importance in various sectors such as medicine, agriculture, manufacturing, construction, transport and communications, these technologies are also extremely promising from the ecological perspective.

When patented, nanotechnology is not always explicitly characterized as environmental technology in its technical specifications. However, the fabrication and use of structures at the atomic and molecular scale (Regis 1995) are intrinsically more ecologically sustainable than traditional technologies. Nanotechnology typically uses few resources and can process all types of waste by rearranging their atomic structures and isolating dangerous atoms (Nicolau 1999). This technology is inherently 'green', and its deployment should decrease demand on the natural environment (Banks and Heaton 1995). As it has enormous potential for environmental implications, its economic and commercial importance has been reflected in the increasing number of nanotechnology patent registrations in the USA.

Figure 1 shows the annual numbers of nanotechnology patents registered at the US PTO from 1975 to 1998. The group of nanotechnology patents was defined by using keywords[3]. Patent registrations refer to the date of patent application, not the date of patent issue, as the former is considered to be a more accurate measure of patent activity (for further explanations, see Chan *et al* 2001, Marinova and McAleer 2002a, 2002b). There is a significant delay between the date of application and the date of issue of patents, in some cases up to 10 years. Consequently, the data for 1999–2001 are still largely incomplete, and are not included in the annual totals in figures 1 and 2.

The number of registered nanotechnology patents in the USA in figure 1 increased exponentially from 305 in 1975 to 4467 in 1995, but with a significant reduction to 3642 in 1996. Although the numbers increased after 1996, US nanotechnology patents for 1997 and 1998 at 4313 and 4376, respectively, were still lower than at their peak in 1995. However, as it takes an average of two years for a patent application to be approved (United States Patent and Trademark Office (USPTO) 1997), it is expected that the numbers of patents for the last 2–3 years of the sample period may eventually be higher than their present levels.

Obviously, nanotechnology is an area of significant patent activity in the mid- to late-1990s. It is interesting to note that the annual share of US nanotechnology patents to total US patents has also been increasing (see figure 2), with a highest share of 2.9% in 1995. Consequently, this group of technologies is becoming increasingly important for the economy. The correlation between the annual US nanotechnology patents (figure 1) and the annual share of nanotechnology patents to total US patents (figure 2) is 0.98, while the correlation between the annual US nanotechnology patents and total US patents is even higher at 0.99.

[3] The main keyword used to extract the data is 'nano$'. However, words related to nanoseconds and the chemical compound NaNO were excluded from the search.

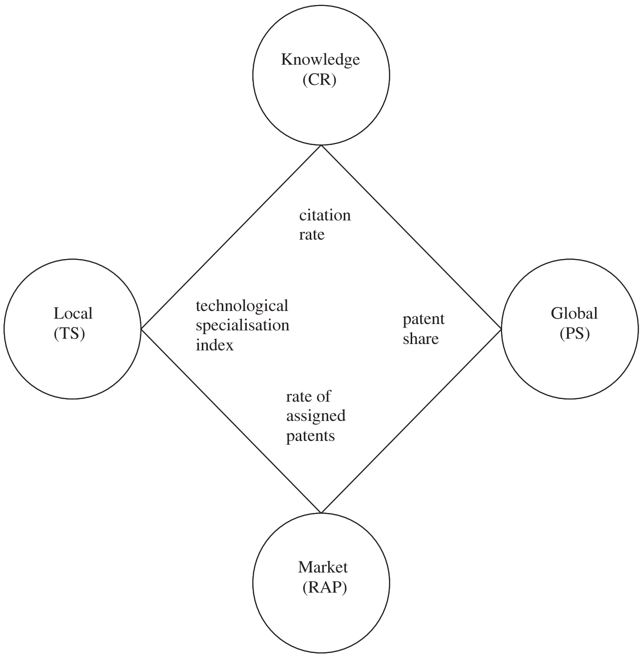

Figure 3. Technological strength indicators based on patent statistics.

3. Technological strength indicators

The patent system is an integral part of national innovation systems (Freeman 1988, Lundvall 1992, Nelson 1993, Edquist 1997), and provides powerful information for measuring the innovative performances of countries and industries (Soete 1987, Patel and Pavitt 1994). Owing to their richness, completeness, longitude and availability, the importance of patent data for research on invention, innovation and R&D policy has been emphasized by scholars such as Pavitt (1988) and Griliches (1990). According to Griliches (1990, p 1661), '[i]n this desert of data, patent statistics loom up as a mirage of wonderful plentitude and objectivity. They are available; they are by definition related to inventiveness, and they are based on what appears to be an objective and only slowly changing standard'. Therefore, patent information has been intensively used to describe national strengths and weaknesses in various technological areas (Campbell 1983, Patel and Pavitt 1991), and to map technological trajectories (Liu and Shyu 1997). Information on patents can also reveal early trends in technological change and is indicative of technological activity, which can subsequently be transformed into market success (Ernst 1997). TSIs, which are used to assess a country's potential in nanotechnology, exploit information contained in patent data (for further details, see Marinova (1999)).

Figure 3 provides a graphical representation of the TSIs which are based on patent statistics. There are four components, represented solely in terms of technological strengths, namely:

(i) contribution of patents to further knowledge development (or knowledge);
(ii) potential economic benefits (or market);
(iii) national priorities (or local) and
(iv) international presence (or global).

The TSIs are based on patent statistics and can be used to assess the technological strengths of a country, region, industry sector or an individual company.

Local and global components reflect the development of technologies and patents themselves. Evidence from innovation studies stresses the importance of two co-existing relationships in the development of technologies, namely globalization and localization (Pavitt 1995). Locally developed skills and knowledge benefit from the interrelated global technological developments and economy, while global technological innovation is given a context in the innovation milieux and local creativity.

The knowledge and market components indicate the potential power of patents. By their nature, patents represent both advancement of knowledge and potential tools for exploiting economic and commercial benefits. However, this does not occur automatically, and registered patents can remain unused for extended periods for a variety of reasons. If a patent (or cluster of patents) provides a technological strength, it will have to manifest its potential explicitly, such as through a contribution to further knowledge development and/or commercialization.

Four patent-related indicators are used to evaluate technological strengths. At the country level, which is the focus of this paper, the TSIs are given as follows.

(1) *Local.* The technological specialization (TS) index is a measure of the local development of technologies, or the comparative advantage of a local technology relative to international standards. Paci *et al* (1997) stress the informative value of the index, which accommodates sectoral differences in patenting in the domestic (or local) economy compared with the world (or global) economy. The TS index is given as follows:

$$\mathrm{TS}_{ij} = \left(P_{ij}/\sum_i P_{ij}\right)/\left(\sum_j P_{ij}/\sum_i\sum_j P_{ij}\right)$$

where P_{ij} denotes patents in sector i (such as nanotechnology) invented by residents of country j. The ratio $P_{ij}/\sum_i P_{ij}$ denotes patents in sector i for country j relative to all patents in country j, whereas the ratio $\sum_j P_{ij}/\sum_i\sum_j P_{ij}$ denotes total patents for sector i in all countries relative to all patents in all countries. Therefore, TS_{ij} reflects the relative strength of sector i in country j to sector i in all countries. If $\mathrm{TS}_{ij} > 1$ for sector i in country j, this represents a technological strength at a national level compared with international standards. The higher the value of TS_{ij}, the greater the relative technological advantage.

(2) *Global.* An indicator of the global impact of technologies in a given field (Patel and Pavitt 1991) is the patent share (PS) of a particular technology in a given country to total patents in the same field, namely

$$\mathrm{PS}_{ij} = P_{ij}/\sum_j P_{ij} \qquad (0 \leqslant \mathrm{PS}_{ij} \leqslant 1)$$

where PS_{ij} denotes the patent share in sector i of country j to total patents in the same sector across all countries.

(3) *Knowledge.* The citation rate (CR) measures the usefulness of a patent in subsequent patent documents, and

hence in the creation of new knowledge. As an indicator, the CR is calculated relative to the total number of patents granted in a given sector or country, as follows:

$$\mathrm{CR}_{ij} = C_{ij}/P_{ij} \qquad \text{or} \qquad \mathrm{CR}_j = C_j/P_j$$

where C_{ij} represents the number of citations for all patents issued in sector i of country j, $C_j = \sum_i C_{ij}$ is the total number of citations for all patents in country j and $P_j = \sum_i P_{ij}$ is the total number of patents in country j. The higher the CR, the more frequently cited the patents. Compiling CR from the US PTO's Internet database is an extremely labour intensive exercise, requiring each US patent to be checked against subsequent US patents for referencing. For industries where the number of patents is far greater than for nanotechnology, CR could best be estimated using sampling techniques.

(4) *Market*. When a patent application has been approved and a patent subsequently issued, the applicant has the right to assign the commercial exploitation of the patent to individuals and/or companies in one or more countries. The rate of assigned patents (RAP) in a given field is a measure of the (perceived) proximity of patents to commercial exploitation (Marinova 1999). When a patent is assigned, the legally protected prototype is closer to commercialization, and assigned patents are thought to have a greater chance of being profitably commercialized (Firestone 1971). Although this does not mean that an unassigned patent cannot be commercially exploited, assigning a patent indicates an explicit intention to use it for commercial purposes. The rate of assigned patents is given by

$$\mathrm{RAP}_{ij} = \mathrm{AP}_{ij}/P_{ij}$$

where AP_{ij} is the number of patents in sector i assigned to residents of country j. As a ratio, the RAP_{ij} is equal to zero when there are no assigned patents in sector i of country j, and equal to unity when the number of patents in sector i assigned to country j is equal to the number of patents in sector i invented by residents of country j. The rate can exceed unity when $\mathrm{AP}_{ij} > P_{ij}$, such as when patents in sector i invented by residents of non-j countries are assigned to individuals and/or companies in country j.

None of the patent statistics incorporated in the TSIs has a time dimension. Such strengths can be established over an extended period when patents are evenly spread, or over a relatively short period when there is high concentration of patents. For example, as relatively small but rapidly increasing contributors to nanotechnology, if Taiwan, Korea and Australia are to demonstrate technological strengths in their development, it will be primarily on the basis of the high patenting activities which have occurred since 1998.

It is important to distinguish between technological and commercial strengths because the latter does not necessarily follow from the former. For example, Narin *et al* (1987) found that patent data are positively correlated with various measures of a company's technological strengths but not with their financial performance. Suppose a country is successful at developing bio-technologies, particularly recombinant DNA techniques. Whether it will also be in a position to develop the associated commercial capabilities would depend on the appropriability of the technology, that is, whether it is possible to exploit the commercial benefits. The national system of innovation, government regulations and social ethics, among other factors, play important roles in such commercial exploitation.

4. International rankings in nanotechnology

Table 1 presents the values of three of the TSIs used in figure 3 in the case of nanotechnology, namely the TS index, PS and RAP, for the top 12 foreign patenting countries in the USA. The three indicators have been calculated using data from the US PTO for the period 1975 to 2000. Even though annual data for 1999–2000 are incomplete, the aggregate data for the 1975–2000 period allow for a reliable comparison between the countries according to the total number of approved patents on the date when the data were extracted (namely 5 March 2002). Patents by US inventors have not been included in the analysis because of limitations in the search engine of the US PTO site[4], and the domestic nature of these patents[5].

From the top 12 foreign patenting countries in the USA, namely Japan, Germany, France, Canada, Switzerland, Italy, the Netherlands, Taiwan, Sweden, UK, Korea and Australia (see Marinova 2001, McAleer *et al* 2002), Japan has the highest number of nanotechnology patents for 1975–2000 at 3856 (see table 1), or 34% of the total patents held by these countries. France is second with 1817 (16%) and Germany is third with 1524 (14%). The performance of the 12 countries is quite different when compared on the basis of patent intensity (number of patents per million of population in 2000). Switzerland is first with 69 nanotechnology patents/million (three times the mean value) and Canada is second with 40 (see table 1). France and Japan maintain relatively strong positions, respectively, in third (with 31) and fourth (with 30) places. Germany, however, drops to seventh place with only 19 nanotechnology patents/million.

France has the highest TS index of 1.42, which indicates an existing specialization and *local* importance of nanotechnology for this country. This is followed by Australia with 1.38, Great Britain with 1.37 and Canada with 1.33. Thus, at the national level, these four countries are concentrating R&D efforts and producing nanotechnology inventions at a higher rate, and with greater strength, than for the mean patent specialization in nanotechnology. None of the remaining countries has a TS index higher than unity. Moreover, the mean TS value is 0.84, which shows that nanotechnology is not, in general, of particular local importance for this leading group of countries.

The PS of total US nanotechnology patents for Japan is 9.05%, France 4.26% and Germany 3.57%. Half of the countries (namely, the Netherlands, Italy, Australia, Taiwan, Sweden and Korea) have a PS of less than 1%, and account for less than 4% of US nanotechnology patents. If a country

[4] The US PTO site does not allow for a straightforward search of patents with inventors residing in the USA. Instead, it requires the search to be performed by state of residence which, combined with the word limitation on the search string, leads to multiple counting of patents.

[5] Inventors tend to patent only their 'best' technologies in a foreign country, while they patent a larger number of technologies domestically (see, for example, Tsuji 2002).

Table 1. Strength indicators for US nanotechnology patents by country, 1975–2000. (Notes: (1) The data were extracted on 5 March 2002; (2) the patent intensity is given per million of population in 2000.)

Country	Number of patents *P*	Patent intensity (PI)	TS index	PS	RAP
Japan	3856	30	0.51	9.05	0.97
France	1817	31	1.42	4.26	0.85
Germany	1524	19	0.50	3.57	0.74
Canada	1249	40	1.33	2.93	0.48
Great Britain	603	10	1.37	1.41	0.55
Switzerland	502	69	0.83	1.18	0.55
Netherlands	384	24	0.89	0.9	0.59
Italy	334	6	0.62	0.78	0.66
Australia	313	16	1.38	0.73	0.75
Taiwan	253	11	0.40	0.59	0.88
Sweden	179	20	0.44	0.42	0.70
Korea	175	4	0.44	0.41	0.81
Mean	932	23	0.84	2.19	0.71

Table 2. Citations and shares of US nanotechnology patents, 1975–2000. (Note: the data were extracted on 5 March 2002.)

Country	CR (rank)	CR for cited patents (rank)	Maximum citations for a single patent (rank)	PS since 1998 (%) (rank)
Canada	6.00(1)	9.22(2)	106(4)	22(9)
Switzerland	5.82(2)	9.94(1)	136(3)	22(9)
Netherlands	5.00(3)	7.48(4)	52(8)	17(11)
Sweden	4.95(4)	8.53(3)	49(10)	25(7)
Japan	4.59(5)	6.82(5)	149(2)	26(5)
Germany	4.17(6)	6.64(7)	87(5)	24(8)
Italy	3.89(7)	6.65(6)	62(7)	3(12)
France	3.88(8)	6.63(8)	283(1)	26(5)
Taiwan	3.40(9)	6.28(10)	36(11)	52(1)
Australia	2.75(10)	6.43(9)	50(9)	48(3)
Great Britain	2.63(11)	6.06(11)	64(6)	40(4)
Korea	2.35(12)	5.51(12)	30(12)	49(2)
Mean	4.12	7.18	92	29.5

is aspiring to have any impact on the global development of this class of technologies, such a contribution needs to be significantly higher.

The RAP, which is an indication of the proximity of patents to commercial development and export orientation, is 0.97 for Japan, 0.88 for Taiwan and 0.85 for France. These countries appear to have strong market aspirations in nanotechnology patenting in the US. Protecting intellectual property in nanotechnology for Canada, Great Britain and Switzerland, which have the lowest RAPs, does not appear to be particularly aggressively market oriented.

Of the four factors comprising the TSIs, the patent CR does not seem to have been analysed empirically in the literature. Although containing useful information, CR seems to be highly sensitive to patent novelty. For example, if a patent has been recognized only recently, it would be unrealistic to expect it to have an influence on technological development, and hence to be well cited in subsequent patent applications. This is particularly so for the bulk of nanotechnology patents. Close to a majority of recognized patent applications from Taiwan (52%), Korea (49%) and Australia (48%) have been lodged since 1998, with the patents subsequently issued in 1999, 2000 and 2001 (see table 2). Not surprisingly, such recent patents presently have a low value of CR.

Table 2 presents the CR values for the top 12 foreign patenting countries in the USA. The mean CR is 4.12, with Canada and Switzerland having the largest mean citation per patent of 6.00, and 5.82, respectively. When CR is calculated only for cited patents, the top two countries still remain ahead of the other ten countries, with a CR value of 9.94 for Switzerland and 9.22 for Canada. The four lowest ranked countries in table 2 have had around 50% of their nanotechnology patents lodged since 1998, which is not sufficient time for citations to occur in subsequent granted patents. For established nanotechnology patents, France is clearly the leader for the maximum number of citations for a single patent at 283, followed by Japan with 149 and Switzerland with 136.

It is interesting to note that the two countries for which patents have been most widely cited, namely Canada and Switzerland, do not rank among the top three countries according to the other three TSIs. Hence, the contribution of these two countries is largely in further technological knowledge development.

Table 3 shows the rankings of the top 12 foreign patenting countries in the USA according to the four indicators, namely TS, PS, RAP and CR, as well as their overall mean rank score. France is first, followed by Japan and Canada, with these three countries having the strongest performance of the top 12 nanotechnology patenting countries outside the USA. The performance of France is particularly outstanding as this country ranks among the top three countries in three

Table 3. Ranking of countries for US nanotechnology patents, 1975–2000. (Note: the data were extracted on 5 March 2002.)

Country	TS	PS	RAP	CR	Mean	Mean score rank
France	1	2	3	8	3.5	1
Japan	8	1	1	5	3.8	2
Canada	4	4	12	1	5.3	3
Germany	9	3	6	6	6.0	4
Netherlands	5	7	9	3	6.0	4
Switzerland	6	6	10	2	6.0	4
Australia	2	9	5	10	6.5	7
Great Britain	3	5	10	11	7.3	8
Italy	7	8	8	7	7.5	9
Sweden	10	11	7	4	8.0	10
Taiwan	12	10	2	9	8.3	11
Korea	10	12	4	12	9.5	12

of the four indicators, and is in the middle range for the fourth. Japan ranks extremely highly in two of the four indicators, but the development of nanotechnology does not appear to be a national priority. The strength of Canada is in citations and further technological knowledge development, while immediate commercialization of the registered patents does not appear to be as important. The Netherlands and Switzerland have high CRs, Australia and Great Britain have high TS indexes and Taiwan and Korea have high values of RAP.

5. Conclusion

Nanotechnology is expected to have significant impacts on society, the economy and the environment. TSIs were shown to be a useful tool in assessing the potential in the field of nanotechnology. The TSIs based on patent statistics, as applied to the top 12 foreign patenting countries in the USA, revealed different emphases in the development of nanotechnology.

Based on the empirical evidence, the best performing country is France, with TS of 1.42 (the highest in the group of 12 non-US countries), PS of 4.26% (second), RAP of 0.85 (third) and CR of 3.88 (eighth). Although ranking very highly in PS (first, with 9.05%) and RAP (first, with 0.97), Japan is second in the overall ranking as nanotechnology is not a national priority (eighth in TS, with 0.51), and its CR is just above the mean (fifth in CR, with 4.59). Canada is ranked third overall, with the highest CR of 6, TS of 1.33 (fourth), PS of 2.93% (fourth) but the lowest RAP of the 12 countries at 0.48.

There are some similarities in the remaining nine countries. For example, nanotechnology appears to be a national priority for Australia and Great Britain (being ranked second and third in TS, with 1.38 and 1.37, respectively). Taiwan and Korea are very much market oriented, with RAP of 0.88 and 0.81, respectively, ranking them second and fourth. Switzerland, the Netherlands and Sweden seem to have a larger impact on technological knowledge development, with CR of 5.82, 5.00 and 4.95 respectively, ranking them second, third and fourth. Italy is in the middle of the range for all indicators, as is Germany (with the exception of a high PS, for which it is ranked third).

The findings of this paper demonstrate that the expertise and strengths in nanotechnology are not evenly distributed among the most technologically advanced countries, which approach these developments with different national strategies and priorities. Some countries are clearly more successful than others according to different indicators, and are currently establishing the foundations for the future impact of this new group of technologies.

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