This is a pre-print of an article published in *Journal of Nanoparticle Research.* The final authenticated version is available online at: https://doi.org/10.1007/s11051-013-2152-x

Trends in nanoscience, nanotechnology and carbon nanotubes: a bibliometric approach

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Keywords: Carbon nanotubes, graphene, nanotechnology, nanoscience, Web of Science, Journal Citation Index

Abstract. Carbon nanotubes are currently one of the most important materials due to their strong mechanical resistance, light weight and transport properties. Since the publication of Ijima's paper on tubular carbon structures (Iijima 1991), approximately 80,000 research articles have been published according to the ISI Web of Science (WOS) database, using "carbon nanotube*" as the search criterion in the search by topic option. In this work, the development and impact of nanoscience and nanotechnology (N&N) and carbon nanotubes on several research areas, journals, specific papers and emerging research areas are analyzed and discussed. Considering the production of papers in these areas from 1997 to 2012, quantitatively speaking, the People's Republic of China is emerging as the leading country in N&N and carbon nanotube research, passing the United States of America. Web of science (WOS) data analysis of nanoscience, nanotechnology and carbon nanotube research in developed and developing countries is discussed, and some ideas for accelerating the progress in these important research areas are proposed.

Introduction

To study the development of a certain field or subject, some researchers have used a bibliometric approach (Terekhov 2009; Subbramanian et al. 2010; Rafols and Meyer 2010; Meyer et al. 2010; Chen and Guan 2011; Motoyama and Eisler 2011). However, due to the enormous number of research articles in the field of nanoscience and nanotechnology (N&N), the detailed study of N&N or carbon nanotubes is a difficult task. For instance, more than 500,000 research articles related to these fields have been published to date, making the task of closely analyzing the state of art of N&N an unrealizable goal. The multidisciplinary aspects of N&N complicate the situation, and certain search criteria are needed to focus on the required data. Trends in different topics related to N&N could be used to determine the progress of N&N. Nevertheless, although it has been severely criticized because its limited database of research publications, the existing modern database of ISI Web of Knowledge allows for the exploration of a specific subject. Researchers have used several methods to obtain more targeted results (Milojevic 2012). For instance, a panorama of N&N research in Mexico has been recently published (Robles-Belmont and Vick 2011).

In this work, the word “nano” and the phrase “carbon nanotube*” are used as search criteria in the Web of Science (WOS) database for the fields of N&N and carbon nanotubes, respectively. For both topics, the “title” option of the WOS database was searched unless otherwise stated. First, a general perspective of the development of N&N and its main recent trends is presented. Then, a view of carbon nanotube research scenario is provided.

Nanoscience and Nanotechnology

The field of nanotechnology emerged with Ijima’s paper about carbon nanotubes (Iijima 1991). There are several published research articles about nanotubular materials that predate Ijima’s paper, but they did not attract the attention of the scientific community in the same way at the time of their publication. Regarding the topic of nanoscience, its emergence can be dated to the famous speech by Richard Feynman given on December 29, 1959 at the annual meeting of the American Physical Society at the California Institute of Technology (Caltech). Compared with nanoscience, nanotechnology is the more frequently mentioned field when searched for in some databases. For instance, searching the ISI Web of Science (WOS) database reveals an enormous difference between the two concepts through the years, as shown in Fig. 1. (Both nanoscience* and nanotechnology* were searched for using the search by topic option of WOS).

Fig. 1: Number of published research articles from 1996 to 2012. The plotted data were obtained using “nanotechnology*” (red stars) and “nanoscience*” (black spheres) as search criteria in ISI Web of Science (WOS).

This discrepancy is expected, considering that nanotechnology is actually a continuation of microtechnology. However, in general, we are still developing in a microworld; it is not yet a nanoworld. An important question that arises in this context is whether nanoscience and nanotechnology are actually a revolution. For instance, if the word “microtechnology” is searched for in Google, approximately 130,000 results are displayed. In the case “nanotechnology”, more than 20 million results are displayed. The situation is more or less the same for “microscience” and “nanoscience”; approximately 400,000 and 7 million results are displayed, respectively. However, using WOS, the results are relatively different but reflect the current status of the disciplines. Fig. 2 shows the trend of published research articles in which the words “micro*” (black circles) and “nano*” (red stars) appear in the title. It is clear that the nanoworld has only recently started to become important in science (see black circles in Fig. 2). In this context, we can state that N&N is beginning to have relevance in science as far as published papers are concerned. As previously mentioned, in the rest of this article, the criterion for searching is the simplest possible: words are searched for using only the title option.

Fig. 2: Plot depicting the number of published research articles from 1996 to 2012 in which the word “micro” or “nano” is included in the title according to the WOS database. Notice that the gap between the two topics has decreased in recent years.

Published research articles

One interesting fact about the development of N&N concerns the number of papers published by country per year. This figure could provide information about the state of the art in each country. For example, Fig. 3 shows the total number of research papers published in several countries from 1997 to 2012 according to WOS. Unquestionably, the data indicate that the USA and China are the leading countries in nano systems research. Japan, Germany, South Korea, India and France can be considered countries positioned in second place in terms of scientific literature production (see Fig. 3a). In third place are England, Russia, Taiwan, Italy, Spain, Iran and Canada. Although, the difference between the second and third places is relatively small, it is possible to discern a difference in production volume. A fourth group is formed by Singapore and Australia (see Fig. 3b). Beyond the fourth group, it is difficult to countries with lower production because the number of papers published in those countries is linearly decreasing. Such countries include Switzerland, Brazil, Poland, the Netherlands, Sweden, Belgium, Israel, Ukraine, Romania and Mexico, among others. The results for this robust group are shown in Fig. 3cb. The superiority of Spain in terms of published research articles is clearly observed; Spain is followed by Brazil, Mexico, Portugal and Argentina. The last set of countries inside the Ibero-America group includes Colombia, Venezuela, Cuba, Uruguay, Peru and Costa Rica, which show low production (see Fig. 3c).

Fig. 3: Number of research articles published in different countries; the number above the column is the rank of each country according to total production. **(a)** USA and China published more than twice as many articles as other developed countries such as Japan, Germany, South Korea, India and France; **(b)** the second group of countries, with the number of papers published ranging between 3,000 and 10,000; **(c)** –Ibero-America group. Note that the scales between (a) and the others are different by an order of scale.

Fig. 4: Evolution of number of research articles published per year. The word used in the search was "nano*" under the "title" option; **(a)**, **(b)** and **(c)** represent data for the countries ranked in the first 13 places; **(d)** considers only some Ibero-American countries, not including Spain.

Before discussing the state of carbon nanotube research, a general description of the evolution of nanoscience and nanotechnology research ("nano*" in the titles of papers) from 1997 to 2012 is provided. Fig. 4 shows this evolution in different countries. Fig. 4a depicts the results for USA (black circles) and China (red stars). Note that in the last 3 years, USA has published fewer papers than China. In Fig. 4b, the respective situation is presented for Japan (black circles), Germany (red stars), South Korea (green squares), India (blue triangles) and France (wine diamonds). It is clear that France's development, although increasing, is growing at the lowest rate in this group. In contrast, France and India are increasing their rate of publishing articles. In 2012, India published the most papers in this field. The evolution of Japan is interesting as well: there has been no increase in their number of papers published per year over the last 6 years. Why this trend has developed in Japan would be a good question to further explore. Germany has shown continuous growth. The development N&N research in South Korea is very good; since 2010, their behavior has been better than that of France and India and in the last three years better than that of Germany. Fig. 4c shows the astonishing development of nanoscience and nanotechnology in Iran (wine empty circles). The other countries (England, black circles; Russia, red stars; Taiwan, green triangles; Italy, blue squares; and Spain,) have shown moderate progress. Taiwan has recently shown very good progress in developing N&N recently (wine diamonds). Russia, England and possibly Italy are having some problems in increasing their scientific production in N&N. For some Latin American countries and Portugal, Fig. 4c shows the curves of production of research articles during the period of 1997-2012. Brazil has shown a clear advancement in N&N over the last ten years. Similarly, Portugal is another country that is investing more resources in developing nano-research. Mexico is in third place in this group; nevertheless, it is still second in Latin America. The three countries plotted in Fig. 4d (Argentina, Chile and Colombia) are increasing their production in scientific articles, which is very good for the continent.

Fig. 5: Plots of the number of nano-research papers published from 1997 to 2012 according to research area. **(a)** Research areas related to N&N and in which most of the papers are published; **(b)** same as **(a)** but presenting a group of recently emerging research areas in the field of N&N.

Research areas

At the beginning of the 1900s, Prof. Leopoldo Maximo Falicov visited the Institute of Physics of the Autonomous University of San Luis Potosí in Mexico. He gave an interesting talk about the future of science. He divided the last three centuries into three periods: the chemistry era (1800-1900), the physics era (1900-2000) and what he predicted would be the biological era (2000-2100); his arguments about these stages of science development are associated with energy concepts researched in each era. Prof. Falicov was emphatic about this last century, stating that science should be devoted to investigating the survival of the human species. Life, in all of its manifestations, would be the most important subject to research scientifically. It appears that the prediction of Prof. Falicov is becoming a reality. Fig. 5 displays the number of papers published from 1997 to 2012 in selected research areas. The three giant research areas in N&N are materials science, chemistry and physics (Fig. 5a). After physics is "science technology in other topics" with more than 80,000 papers (not shown), but due to the difficult analysis, the data have been omitted. Engineering is the fifth most productive research area, with papers focused mainly on applications or specific syntheses of materials. This trend possibly indicates that N&N is most appealing as an experimental discipline. It remains to be seen whether this trend will continue to grow with time. It is worth noting that in addition to the 9 main research areas are biochemistry and molecular biology, pharmacology and pharmacy and biotechnology. All of these research areas could be considered emergent in N&N, and there are a relatively large number of studies related to health. To demonstrate the current relevance of the life sciences, Fig. 5b shows 13 other selected research areas that are related to biology. As indicated, fuels, computer science, spectroscopy and nuclear science technology have a similar importance as biophysics, environmental science and ecology, research experimental medicine, toxicology, cell biology, water resources and oncology.

The impact of research represents another parameter that can be used to measure the quality of the N&N field. One way to measure this parameter is to analyze the types of research journals that are dedicated to N&N and their impact factors (I.F.). There are several nano-journals that have been created recently and are closely related to any type of nano-research. However, there are several old journals that are now publishing nano-investigations related to their particular aims and scopes. This situation is important because the interdisciplinary character of N&N is spreading to all sciences. Fig. 6 shows a list of journals that published nano-research papers from 1997 to 2012. As shown, Applied Physics Letters (APL) is the journal that published the most nano-papers. After APL, we found three nano-journals where it is very likely that only nano-related topics are considered (Fig. 6a), namely, Nanotechnology, Journal of Nanoscience and Nanotechnology (J N&N) and Nano Letters (NL). Nano Letters, Journal of American Chemical Society (JACS), Journal of Materials Chemistry and Chemical Communications are journals with impact factors greater than 5.0. Journal of Nanoscience and Nanotechnology has the smallest impact factor in this group of journals (IF = 1.149~~6~~). In the second group (see Fig. 6b), there are only two nano-journals (ACS Nano and Journal of Nanoparticle Research) and more journals than in the previous group have an impact factor greater than 5.0 (Advanced Materials, Chemistry of Materials, ACS Nano, Carbon, Physical Review Letters, Angewandte Chemie International Edition). The impact factor of Advanced Materials Research was not found in the Journal Citation Report (JCR), and Journal of

Applied Polymer Science has the smallest impact factor. In the third group (see Fig. 6c), there are also only two nano-journals (Small and Nanoscale). Small, Nanoscale and Macromolecules have impact factors greater than 5.0. As in the second group, there is one journal, Key Engineering Materials, for which there is no information in the JCR database. In the last group of journals, the most important journals of science in general are included (Nature, Science and Proceedings of National Academy of Sciences). Important journals dedicated to materials research are also included (Advanced Functional Materials, Nature Materials, Biomaterials). In this group, the impact factor is very homogeneous if the largest journals are not considered. In addition, there are no journals with an impact factor less than 4.0, and there are 12 journals with an impact factor greater than 5.0. This group shows good research quality but a relatively small number of published papers.

Fig. 6: Plot showing several journals where nano-papers are published: **(a)** more than 3,500 papers published during the period 1997-2012; **(b)** more than ~2,000 and less than 3,500 papers published; **(c)** between 1,500 and 2,000 papers published; **(d)** between 500 and 600 papers published.

Table 1 shows lists of journals where the USA, China, Japan, Iran and Mexico have published nano-research papers. The USA, China and Japan are the countries that are publishing the greatest number of papers in N&N; Iran is an interesting developing country that is playing a good role in publishing N&N research. Brazil and Mexico are important nations in Latin America. Although the American Chemical Society is the journal where US nano-research results are mostly published, this journal does not have its impact factor listed in the JCR database. Therefore, in this case, APL is going to be considered the journal where most nano-research from the USA is presented. A large number of papers are published in the most important journals (NL, JACS, ACS Nano, PRL, Chemical of Materials and Advanced Materials). The USA has an average impact factor of 6.4446 when considering only the top 14 nano-research journals where nano-papers are published. In all cases, the average impact factor (AIF) was calculated by multiplying the total number of papers published by each journal by the impact factor and dividing the product by the total number of nano-research papers published. In China (column 2 in Table 1), only two important journals report the results of nano-research from this country (Journal of Materials Chemistry and Chemical Communications); the relevance of the research published in Advanced Materials Research is not yet known. The average impact factor of China is 3.063, considering the 14 journals listed in column 2. China has a national nano-journal, Chemical Journal of Chinese Universities-Chinese, which has with an I.F. of 0.735619. The list of journals for Japan is similar to that of the USA, but NL and JACS are not in the same place. NL is not included in the list of the top 15 most relevant journals where mostly nano-papers are published; only JACS and Chemical Communications, with good impact factors, are included. The average impact factor of Japan is 3.148. Japan's national journal, Japanese Journal of Applied Physics, has an I.F. of 1.058. In the case of Iran, the average impact factor based on the top 15 journals is 1.783~~849~~ (column 3 in Table 1), with Electrochimica Acta (I.F. 3.777~~832~~) as the highest-quality journal and Asian Journal of Chemistry with the worst impact factor (I.F. 0.253~~66~~). The national journal, Journal of the Iranian Chemical Society, has an I.F. equal to 1.467~~689~~. This figure is very good considering the impact factors of the other journals. Brazil is progressing well in publishing in good journals, following in the steps of the USA and Japan. The country has 8 journals in common with USA and Japan among the top 15 journals with the largest number of published nano-papers. PRL is one of these 15 journals, which is a very good journal where important physical results about nanomaterials are published. Brazil has an average I.F. equal to 2.989~~771~~. One of its national journals, Journal of the Brazilian Chemical Society, has an I.F. equal to 1.283~~434~~. Brazil's other national journal among its 15 best nano-journals is Quimica Nova, but this journal has an I.F. of only 0.737~~63~~. Mexico has an average I.F. of 3.124~~85~~. This large I.F. is related to the fact that among the top 15 nano-journals with the highest number of articles published is Nano Letters, with an I.F. equal to 13.198. The national journal in Mexico, *Revista Mexicana de Física*, has an I.F. equal to 0.366. In general, Mexican researchers prefer publishing in good-quality journals. Journal of Nano Research is another journal that is mostly used by Mexican researchers to report their nano-research results.

Another trend worth noting is the evolution of the number of papers published in these journals in recent years. Fig. 7 shows this development since 1997. In terms of publishing papers, NL started in 2001, and its number of papers has been increasing; however, the establishment of ACS has had some effects on this development (see Fig. 7a). According to Fig. 7a, Chemistry of Materials and PRL are being affected by the enormous growth of ACS Nano. Chemical journals such as JACS are excellent journals in which nano-research is one of the strongest topics but not the only one. Fig. 7b shows the progress of four excellent journals (Angewandte Chemie International Edition, Small, Advanced Materials and Biomaterials); similar to NL, Small has felt some effects from the rapid growth of ACS Nano, but these effects have not been drastic. It should be noted how Biomaterials rapidly has increased its number of published papers since 2008. Interesting behavior is shown in Fig. 7c, where Journal of Nanomedicine, Nanomedicine and Soft Matter and Biosensors show an astonishing increase of their number of published nano-papers since 2009, 2006, 2007 and 2006, respectively. Because the last data points were taken at the beginning of March 2012 for the last two journals, the figures do not represent the final totals. At the time when this article is published, it is likely that the points for Biosensor and Soft Matter will indicate a greater number of published papers. In the last group of journals, Nature Nanotechnology is the most notable according to Fig. 7d; Nature and Science maintain their respective number of papers published on nano-research. PNAS is an excellent journal showing increasing growth, in contrast to Nature Materials, which appears to be publishing fewer papers.

Fig. 7. Plots showing the evolution of the number of nano-papers published from 1997 to 2012. In (a), (b) and (c), only the most important nano-journals are considered. In (d), Nature, Science, PNAS and Nature Materials are taken into account to compare with Nature Nanotechnology, the most important journal in N&N.

The general situation regarding N&N has been presented above; the main goal was to demonstrate the general trends of these fields in the scientific world. The only aspect analyzed was the number of published nano-papers according to the WOS. The method used to select the nano-papers was simply to consider papers that include the word "nano*" in their title (with asterisk). Some problems could be associated with this method, but the aim was only to show a general trend, not to provide deeper insight into the state of N&N. Although the USA has recently published fewer nano-papers than China, the USA continues to be the country producing the highest quality of research. Brazil and Mexico are countries that publish a relatively low number of papers, but at their level of production Mexico and Brazil, tend to select the best journals to publish their nano-research results.

Carbon nanotubes

One of the most fundamental materials synthetized and characterized in N&N is carbon nanotubes (CNTs). Since Iijima's paper was published (Iijima 1991), the number of papers concerning research about this material has increased enormously. However, in the last three years, as a result of the synthesis of graphene (G), this situation has changed dramatically. In Fig. 8, the number of CNT papers and G papers published since 1997 is presented. The data were obtained in two ways: i) searching for "carbon nanotube*" in the title and ii) searching for "carbon nanotube*" as a topic. The same method was used to obtain the plots for G. As shown, the G curves do not change substantially in either the topic or title case, but the CNT curves show a larger difference when one or the other criterion is used to obtain the data. This result may be because in the case of G papers, it is practically necessary to use the phrase "carbon nanotube*" in a manuscript, which could be the reason that the star curve (CNT topic case) in Fig. 8 does not show a drop. However, if "carbon nanotube*" is searched for only in the title (which indicates that nearly 100% of the papers will refer to CNT research), the situation is completely different and the number of papers increases slowly and possibly remains stagnant after 2009. Large differences are observed in the CNT case. In the title-searching case, the number of graphene papers is larger than the number of CNT papers in 2012. It is possible that carbon nanomaterials science is entering the era of graphene. It should be recalled that at the beginning of this article it was established that the method used here is searching by key word (carbon nanotube*, graphene, etc.) only in the titles of papers unless otherwise stated.

Fig. 8. Number of papers published over the period 1995-2012 that satisfy the following conditions: i) carbon nanotubes occurs as a topic (red stars) or ii) as part of a paper title (black circles); iii) graphene occurs as a topic (blue squares) or iv) as part of a paper title (purple diamonds).

Fig. 9. Number of papers published by different countries related to CNT (solid red columns) and G (green patterned columns): (a) Countries with the most number of papers published in this period; (b) some Ibero-American countries.

A general description similar to that provided for the case of N&N will be presented for carbon nanotubes. Additionally, for further clarification, the states of CNT and graphene research will be compared. Fig. 9 shows the number of CNT and G papers published by different countries from 1997 to 2012. The graph describing the countries with the highest number of articles published (Fig 9a) on CNT research shows some differences relative to the N&N case. For example, South Korea is now the fourth most productive country instead of Germany; Russia is 13th, below Spain and Iran. With respect to publishing graphene research, China is first and South Korea third; Spain has published more G papers than India, Italy, Iran and Russia. In the Ibero-American group, Brazil is still the most productive country in terms of both CNT and G papers published in this period. Mexico is still the second most productive nation in publishing CNT papers but third in publishing G papers, and very close to Mexico is Argentina. Portugal is showing very strong scientific progress in publishing G papers. It appears that Venezuela is not particularly interested in this new carbon material, unlike Uruguay, which has published more G papers than CNT papers.

The results presented in Fig. 9 represent the total cumulative number of papers published since 1997. However, currently, the situation is changing at a relatively fast speed (see Fig. 10). For instance, Fig. 10a shows how the pace of research in carbon nanotubes* has been slowing down since 2009 in the USA. Nevertheless, in all curves shown in Fig. 10, the last point presented for 2012 could actually be larger because it was obtained at the beginning of March 2013, when the actual data for 2012 had not yet been included in the database of WOS. However, the trend observed for the USA is declining and that for the other countries likely increasing, except for Japan, whose scientific production in this field has been constant since 2008. It is clear that the number of papers published by China has been greater than that published by the USA since 2010. China is showing good progress in CNT and G research as well (see Fig. 9a). Fig. 10b shows how India and Iran are the most enthusiastic countries in producing research papers about CNT. Nevertheless, the state of N&N research in England is an interesting subject to consider (see Fig. 4c); in the case of carbon nanotubes, it appears that the field is not as important as it was in 2008 (see Fig. 10b). Spain, Italy and Taiwan have continued their progress over the past 4 years, having been clearly affected by the graphene phenomenon. For the Ibero-American countries presented in Fig. 10c, the trend observed for the publishing of CNT papers is peculiar: As is the case for N&N research, Brazil is the leader in CNT research, but the data show some fluctuations in this respect, which may have possibly been due to the development of graphene; however, the last three data points indicate that the situation has normalized. CNT research in Portugal, however, has evolved uniformly (see blue squares in Fig. 10c). Although its number of published papers is the smallest, Argentina has also shown good progress in producing CNT papers (green squares Fig. 10c). Mexico shows an oscillating trend (red stars Fig. 10c), but overall, the situation over the past four years is not encouraging in increasing the number of published CNT papers.

Fig. 10. Number of papers published with "carbon nanotube*" included in their title. In (a) and (b), the countries with the greatest number of published papers are plotted; in (c), the corresponding behavior for four Ibero-American countries are shown.

With respect to journals, CNT papers are mostly published in Carbon (I.F. equal 5.4). APL and PRB are the second and third most popular journals, respectively, among researchers publishing CNT papers (see Fig. 11a). Three nano-journals are among the top 13 journals (Nanotechnology, Nano Letters and ACS Nano). Important chemical journals with good I.F. such as Journal of Physical Chemistry C and B (JPCC or JPCB), Chemical Physics Letters (CPL) and Journal of American Chemical Society (JACS) are also among the top 13 journals and publish many CNT papers. PRL and PRB, two high-quality physical journals, are important journals in this first group. The situation is completely different in the case of G papers; PRB is the journal with the most G papers published from 1997 to 2012. The second group consists mostly of chemical journals such as Journal of Materials Chemistry (JMC), Chemical Communications (CC), Journal of Chemical Physics, Physical Chemistry Chemical Physics (PCCP) and the German journal Angewandte Chemie International Edition (ACIE). Chemistry could be one of the most important scientific areas over the next few years concerning the topic of CNTs. It should be noted that Biosensors and Bioelectronics (BB) is making a relatively important contribution to the CNT field. It can also be observed that JMC is the most demanded journal by G researchers. The last group presented in Fig. 11 includes the most important journal in the N&N field (Nature Nanotechnology) and other important journals concerning general science such as Nature, Science and Nature Communications. Important materials science journals such as Nature Material and Materials Today are also included. It should be noted that the emerging journals Nanomedicine and Nanotoxicology have good I.F. and are becoming noteworthy in the field, though they do not have perceptible numbers of G papers published in them.

Fig. 11 plots showing several journals where CNT and G papers were published from 1997 to 2012. The numbers above the columns are the corresponding impact factors. Three groups of journals have been plotted; (a) the top 13 journals with the largest number of papers published in them; (b) 13 journals selected from the next 50 journals below ACS Nano; (c) 13 journals selected because of their large impact factor.

Fig. 12. Plots showing the number of CNT papers published in 9 important nano-journals. Only 17 countries are considered in this figure. Nano Letters is the most popular journal in the USA for publishing CNT papers

Fig. 12 shows the different countries where researchers are publishing their scientific CNT results; the number inside the parentheses is the impact factor. Fig. 12 shows how Carbon is the strongest journal with respect to CNT research. China, Japan, France, Germany, Taiwan, Italy, Spain, Russia, Iran and Portugal submit to this journal to report scientific results about CNTs (see Fig. 12a and c). As is the case for N&N, the USA is the country with the highest standards of quality for CNT research; NL, ACS Nano, Advanced Materials and Nature Nanotechnology are important journals that are most requested by US researchers for publishing results related to CNTs (see Fig. 12a and b). Nanotechnology is a good journal that is also demanded by CNT researchers from China, the USA, South Korea, England, Spain, India and Iran (see Fig. 12a and c); Journal of Nanoscience and Nanotechnology is one of the most preferred journals by South Korea, Spain, India, Brazil, Mexico and Argentina. Another excellent journal requested by the majority of countries for publishing CNT results is Advanced Materials (see Fig. 12b); China, the USA, Japan, France, South Korea, Germany and England prefer Advanced Materials to publish their CNT results. Spain and India have made a very good contribution to the CNT field with a large number of CNT papers published in Carbon, Nanotechnology and Nanoscale (Fig. 12b and c). It should be noted that Mexico has also made an important contribution to this field, publishing in important journals such as NL, ACS Nano and Small. Brazil is another Latin American country that produces good-quality CNT results; Carbon, NL and Nanotechnology have published a relatively large number of CNT papers from Brazil (see Fig. 12c).

Fig. 13. Number of CNT papers published in various research areas in which important findings about CNTs have been published. The graphene case is shown for comparison.

As shown in Fig. 13, chemistry and materials science are the second most important research areas affected by CNT research, with physics being the principal research area. Biochemistry and molecular biology are emerging areas in which CNT research is having a great impact due to potential applications in medicine and toxicology, as shown in Fig. 13b (biotech AM denotes biotechnology and applied medicine). It should be noted that biophysics, cell biology and neuroscience are including CNT research in their development. Other important emerging areas are environmental science and water research, which are probably related to CNT research in terms of the adsorption of toxic metals.

Upon the development of the N&N field, the importance of emerging nano-research areas related to biology, such as nanomedicine, nanotoxicology, nanopharmaceutical and others, was established. As shown in Fig. 5b and Fig. 13b, these areas are developing very rapidly with an increasing impact on the N&N and CNT areas of study. It is very important that developing countries take into account this situation because it represents the opportunity to become competitive in N&N or CNT research. Several countries that were once regarded as developing countries are now competing at the same level with very strong countries in N&N or CNT research. Carbon nanotube research has the opportunity to progress in the bioscience or biomedicine research areas.

Fig. 14. Plots showing the number of times selected papers were cited from 1997 to 2012. Each curve represents one paper denoted by the name of the first author. In the case that the first author is repeated, the number 2 is added to the name; see, for example, the case of Tans in (a) and (b) or Chen in (c) and (e). It is worth mentioning that the Baughman, *et al.* (2002) paper, which was published in 2002, is still being cited a considerably large number of times. The main contribution of each paper to CNT research is discussed in the main text.

Fig. 14 shows the number of times 26 papers that have contributed substantially to CNT research have been cited. The Baughman, *et al*. (2002) paper was the most cited in the period 1997-2012 with 4658 citations. In this review paper, after discussing different nanotube synthesis and processing procedures, the authors explained the most important future applications of CNTs, namely, CNT composites, electrochemical devices, hydrogen storage, field-emission devices, nanometer-sized electronic devices and sensors and probes. The importance of these applications is confirmed by the number of citations the paper has received (Fig. 14a). The first Tans, *et al.* (1998) paper, published in 1998, is the second most cited publication (3941 times cited) and concerns the fabrication of a field-effect transistor using a CNT. As shown in Fig. 14a, the maximum number of citations received by the paper was achieved in 2006. The Dillon, et al. (1997) paper concerns the storage of hydrogen in single-wall CNTs; with 2473 times cited (TC), this paper, published in 1997, is the third most cited publication. The Fan *et al*. (1999) paper shows a similar trend; published two years after the Dillon et al. (1997) paper, the Fan *et al.* (1999) paper discusses the fabrication and emission properties of regular arrays of multiwall CNTs. Fig. 14b shows the citation trends of four other important papers: a second Tans *et al.* (1997) paper, O'Connell, *et al.*(2002), , Wildoer *et al.* (1998) and Ren, *et al.*(1998) ; except for O'Connell et al. (2002), the others show similar behavior over time; since 2007, the number of citations received by these papers has decreased linearly. The second Tans et al. (1997) paper, with 2115 TC, discusses the fabrication of individual single-wall carbon nanotubes (SWNTs) as quantum wires. The Wildoer,et al. (1998) paper (1905 TC) concerns the electronic properties of CNTs as a function of wrapping angle, and the Ren, *et al.*(1998) paper (1833 TC) presents the fabrication of large arrays of multiwall carbon nanotubes grown on glass for device applications. The citation behavior of the O'Connell, et al. (2002) paper, which discusses fluorescence studies of single-wall carbon nanotubes, is rather interesting. This paper has been cited 2044 times. Following the paper's publication in 2002, the number of citations received per year steadily increased up to 2009 and then began to diminish dramatically. Although the O'Connell, et al. (2002) paper generally has a good number of TC, it appears that it is not as appealing to researchers as it was in previous years. The next four most important CNT papers are presented in Fig. 14c; the Yu, *et al.* (2000) paper deserves some attention due its citation behavior over the period spanning from 2000 (published year) to 2012 (see red stars in Fig. 14c). This paper has been cited 1849 times and is the first article about the mechanical properties of single- and multiwall CNTs. It appears that the mechanical properties of CNTs are still very important for different applications. The other three CNT papers in this plot, Journet, et al. (1997), Chen, *et al.* (1998) and Martel, *et al*. (1998), have become decreasingly important since 2007 (Chen and Martel) and since 2002 (Journet). The Chen, *et al.* (1998) paper was published in 1998 and has been cited 1808 times. The Chen, *et al.* (1998) paper is one of the most important papers about the functionalization of single-wall carbon nanotubes; however, with the advances in this field, the papers importance has recently decreased (since 2008). A field-effect transistor fabricated using individual single- and multiwall carbon nanotubes was presented by Martel *et al.* (1998). This paper is interesting because although it was published in a journal with an impact factor of 3.844, the impact in the nano-scientific community is relatively high. Although this impact diminshed after 2007, the number of times it was cited increased last year (see blue square in Fig. 14c). The paper by Thostenson *et al.* (2001) is a review of the advances made in developing composite materials reinforced with carbon nanotubes. The importance of this subject is evidenced by the fact that since the paper was published its number of has increased steadily; the last data point in 2012 could be due to the last-year effect mentioned previously. In addition, although Composite Science and Technology is a journal with an impact factor of 3.144, the paper by Thostenson *et al.* (2001) has been cited 1702 times. Bachtold and collaborators (2001) were the first group that demonstrated the creation of logic circuits using field-effect transistors based on single-wall carbon nanotubes [bachtold]. The two first two years after it was published, the Bachtold, et al. (2001) paper was heavily cited (see red stars in Fig. 14d). However because 2004, its TC value has gradually decreased. The Bachilo, *et al.* (2002) paper presented an optical spectroscopy route to determining the detailed composition of bulk single-wall carbon nanotubes. With their method, the researchers could determine the distributions of nanotube diameter and chiral angle. Although this paper has received a considerable number of citations, the number per year is rapidly decreasing. The effect on the electrical resistance of single-wall carbon nanotubes was reported for first time by Collins, *et al.* (2000) for gas-sensor applications. This paper has remained an important contribution to the topic of nano-sensors since 2007 (see Fig. 14d). Nano-sensors are a niche opportunity for development over the next few years. In the next group of most cited papers, the Tasis et al. (2006) paper shows a very good trend (red stars in Fig. 14e). The Tasis *et al.* (2006) paper (1602 TC) was published in 2006 and concerns, as the title suggests, the chemistry of carbon nanotubes; specifically, the paper is a review of the chemical functionalization of CNTs. Although it appears that its impact is diminishing, the number of times the paper has been cited is still large. The papers by Javey *et al.* (2003) and Chen *et al.* (2001) both show a similar trend. Javey *et al*. (2003) paper (1513 TC) was published two years after Chen *et al*. (2001) paper (1495 TC); its impact was great at the beginning but has saturated since 2005. The importance of the Chen *et al.* (2001) paper to the scientific community increased linearly and saturated in 2008. Javey *et al*. (2003) presented ballistic carbon nanotube field-effect transistors for first time, and Chen *et al.* (2001) reported on the noncovalent functionalization of the sidewalls of single-wall carbon nanotubes using a bifunctional molecule. This article was published in Journal of the American Chemical Society. Chemistry is beginning to become very important in N&N research, specifically with respect to functionalization. The other two papers in this group are the Rao, *et al.* (1997) and Odom, *et al.*(1998) papers. The Rao, et al. (1997) paper has a TC value of 1559, and that of the Odom, et al. (1998) paper is 1540. Rao *et al.* (1997) reported for the first time theoretical and experimental Raman scattering studies of SWNTs, revealing the normal vibrational modes of a carbon nanotube and specific diameters. Odom *et al.* (1998) reported on the relation between the electronic properties and diameter and helicity of carbon nanotubes. The papers show similar citation behavior, and the treated topic is still important to researchers but to a lower extent than in past years. The last group of papers includes the Zhen *et al.* (2003) paper, which concerns the dispersion of single-wall carbon nanotubes using DNA, opening biotechnology research to carbon-nanotube-based applications. Immediately after being published, the Frank *et al*. paper was very interesting to the CNT community. However because 2008, this situation has change and interest in quantized conductance in CNTs has diminished. Thus, the TC per year of the Frank *et al.* (2003) paper decreased (see black circles Fig. 14f). The Baughman *et al.* (1999) and Kataura *et al*. (1999) papers show interesting behavior. At first (1999), interest in the topic presented in these two papers was increasing, until 2003 when the TC value started to become approximately constant (100 TC). The Baughman *et al.* (1999) paper discussed the use of single-wall CNTs as electromechanical actuators, and Kataura *et al.* (1999) presented an excellent optical study of single-wall carbon nanotubes; it was in this paper that the famous Kataura plot was established. This paper was published in Synthetic Materials, a journal with an impact factor of 1.829. Such topics are currently common and receive approximately 100 citations per year. The Liu *et al.* (1999) paper, similar to the Frank *et al.* (1998) paper, is slowly losing interest among the CNT scientific community. The papers concerns hydrogen storage in single-wall carbon nanotubes at room temperature. It is possible that other materials for hydrogen storage have been more popular than carbon nanotubes (Rosi 2003). The following is an analysis of the most cited articles since 1996.

As shown in Fig. 14, an important and impressive paper with breakthrough findings can continue to be cited for 5 to 10 years after its publication depending on the findings' relevance in the field. In the case of carbon nanotubes, it was observed that only a few papers have remained relevant after more than 10 years. To provide a better view of advances in CNT research, Fig. 15 presents data regarding the 16 most cited papers from 2006 to 2012. Some of the papers have already been plotted in Fig. 14; thus, they are not considered again. Fig. 15a shows data for four important papers. Moniruzzzaman *et al.* (2006) was published in Macromolecules (good impact factor of 5.167) and has been cited 504 times. As shown in Fig. 14a, the impact of the paper is good; the authors discuss polymer nanocomposites containing carbon nanotubes. This subject is has been well received by composite-polymer researchers dedicated to N&N. The paper by Coleman *et al.* (2006) shows a similar trend to that by Moniruzzzaman *et al.* (2006). Coleman *et al*. (2006) reviewed the mechanical properties of carbon nanotubes and the state-of-the-art techniques used to produce polymer-nanotube composites. It is interesting that the mechanical properties of CNTs represent a topic with relatively promising applications. It should be noted that Coleman's paper was published in the excellent journal Advanced Materials, which has an impact factor of 13.887. Kosynkin *et al.* (2009) is a paper related to the recently popular topic concerning the fabrication of graphene nanoribbons by cutting carbon nanotubes. This paper was published in 2009 and rapidly received a larger number of citations. Although nanoribbons can be produced by simpler methods, this paper is still interesting to CNT researchers (see blue squares in Fig. 15a). The citation behavior of the Arnold *et al.* (2006) paper is different from that of the others. Since 2010, interest in the topic presented has declined. The researchers present a method for classifying single-wall carbon nanotubes according to their diameter, bandgap and electronic properties. The second group of these most cited papers is plotted in Fig. 15b. The Poland *et al.* (2008) paper (black circles in Fig. 15b) concernst the possibility that carbon nanotubes present asbestos-like pathogenicity. The topic in this article still continues to be interesting to researchers because of its relevance for human health. In the paper by Holt *et al.* (2006), the researchers addressed the subject of electronic transport through single-wall carbon nanotubes. Interest in this theme has grown over time (see red stars in Fig. 15b), possibly because of its implications in water research. The paper by Coleman, Kahn, and Gun´ko, *et al*. (2006) shows similar behavior to that by Holt *et al.*(2006): the number of citations has grown over (except in 2011; see blue squares). This paper is very similar to the other paper by Coleman *et al*. (2006); it is also a review of the mechanical properties of carbon nanotube–polymer composites. The paper by Jiao *et al.* (2009) discusses the fabrication of narrow graphene nanoribbons obtained from multi-wall carbon nanotubes. Much like the Kosynkin *et al.* (2009) paper, the Jiao *et al.* (2009) paper was cited very heavily at first; however, last year, the paper did not receive as many citations as in previous years. In the third group, it is possible to see the interesting behavior of the Gong *et al.* (2009) paper. The authors present results associated with the high electrocatalytic activity for oxygen reduction of nitrogen-doped carbon nanotube arrays. Due to its enormous importance in fuel cell applications, the paper currently shows a rapidly increasing TC value. In contrast, the papers by Liu *et al*. (2007) and Kang *et al*. (2007) papers have been losing importance in the scientific community since 2010, when their number of citations TC started to drop slightly. Liu *et al.* (2007) report a study of the biodistribution of single-wall nanotubes in mice performed using different biological and Raman spectroscopy techniques, and Kang *et al.* (2007) report on the use of dense, aligned arrays of long single-wall carbon nanotubes as an effective thin film semiconductor suitable for integration into transistors and other types of electronic devices. The trends observed for these papers are due to the considerable advances in nanoelectronics and bionanotechnology. Futaba *et al.* (2006) paper present a method for producing densely packed and aligned single-walled carbon nanotubes by the zipping effect of liquids, which draws tubes together. The trend for the next group of papers is similar, except for possibly the Kostarelos *et al.* (2007) paper (green squares in Fig. 15d). The Singh *et al.* (2006) paper, published in Proceedings of National Academy of Sciences, demonstrated that functionalized water-soluble and biocompatible single- and multiwall carbon nanotubes exhibit significantly improved toxicity profiles compared with their nonfunctionalized counterparts. Wildgoose *et al.* (2006) review the techniques used to functionalize carbon nanotubes with metals and other nanoparticles and their possible applications. Worle-Knirsh et al. (2006) is a paper published in Nano Letters that has been cited 365 times. This paper discusses the study of the toxicity of single-wall carbon nanotubes. Three of the last four papers mentioned have maintained their TC values; they are related to carbon nanotube functionalization, toxicity and biocompatibility, all of which are topics that are very important to carbon nanotube applications. The Kostarelos *et al.* paper (2007) is a Nature paper concerning the use of CNTs in biomedical applications as nanovectors for therapeutic agent delivery. This paper demonstrates the importance of the interaction between cells and CNTs in biological applications. This paper has been cited 408 times, and its TC value increased each year from 2007 (when it was published) to 2011. In 2012, the paper experienced a slight drop in number of citations but generally shows an increasing trend (see green squares).

In Mexico, carbon nanotube research has had an important influence. The most cited study in which a Mexican institution was involved is that by Terrones (2003). With 336 TC since it was published (2003), the paper is number 329 on the list of 47,187 papers related to carbon nanotubes* from 1996 to 2012. This paper is a review of the fabrication, properties and applications of carbon nanotubes. The next paper on this list is by Terrones *et al.* (2002), with 332 TC; in this article, the authors present a theoretical and experimental study of single-wall carbon nanotube junctions, which is an important issue in electronic applications. In third place is a paper by Jiang *et al.* (2003) that presents a study of the decoration of nitrogen-doped carbon nanotubes with gold nanoparticles, a topic with a high impact in delivery drugs and catalytic, electronic, optical and magnetic applications. Following this article is another Terrones *et al.* (2000) paper . This is a Science paper that demonstrates the coalescence of single-wall carbon nanotubes (301 TC). In fifth place is a Czerw *et al.* (2001) paper in which the authors demonstrate that nitrogen-doped carbon nanotubes exhibit band modifications with the contribution of a large electron donor state. Terrones, Ajayan *et al.* (2002) is the next article on the list of most cited papers; in this work, the authors present the fabrication and characterization of nitrogen-doped multiwall carbon nanotubes and also demonstrate, theoretically and experimentally, the coalescence of single-wall carbon nanotubes. Chemistry of Materials is a good journal, with an impact factor of 7.286. In this journal, the seventh best paper according to number of citations, an article by Velasco-Santos et al. (2003), was published. The paper discusses the fabrication of composites using chemically functionalized carbon nanotubes and has been cited 170 times. The next article on the list is a Science article by Sun *et al.* (2006)*;* the authors report on the deformation, extruding and breaking of nanomateriales inside carbon nanotubes by electronic radiation. The Mayne *et al*. (2001) paper is the ninth most cited paper involving a Mexican institution. This paper, published in Chemical Physics Letters (2.337 I.F.), addresses the fabrication of carbon nanotubes using aerosols generated from benzene/ferrocene solutions as chemical sources. The next paper (Jiang 2004) was published in Journal of Materials Chemistry (5.968 I.F.), which is a very good journal. The paper focuses on the attachment of biomolecules to carbon nanotubes under ambient conditions. As shown, the papers involving a Mexican institution are related to diverse topics such as reviews (Terrones 2003); synthesis (Mayne 2001); related carbon nanotubes structures (Terrones et al. 2002, Jiang et al 2003, Terrones et al. 2000, Terrones, Ajayan et al. 2002); physical properties (Czerw et al. 2003, Velasco-Santos et al. 2003, Sun et al. 2006) and biology (Jiang et al. 2004) It is important that in countries such as Mexico research in N&N focuses on important issues with which researchers show extensive experience.

Fig 15. Plots of 16 most cited papers related to carbon nanotube research published over the period 2006-2012. Depending on the issues addressed in the papers, diverse behavior can be observed.

Conclusions.

Nanoscience and nanotechnology are two multidisciplinary research areas with different trends of development and social impact. They are part of a unique scientific and technological revolution. This revolution is currently in its beginning stages. The most important fields in N&N over the next 100 years will be those related to life and its conservation and survival, as predicted by Prof. Falicov. Topics such as nanobiotechnology, environmental conservation, toxicology, nano-medicine and other similar ones will be intensively investigated. To improve the quantity and quality of nano-research findings, developed and developing countries must concentrate on problems associated with the above-mentioned issues. China and the USA are now the leading countries in N&N research. However, there are other nations (*i.e.,* Korea, Taiwan, Spain, Iran)that are rapidly progressing in nano-research and are focusing on nano-biology-related research, making important contributions to the N&N world; nevertheless, it is necessary to enhance the quality of their findings to overcome the usually internal economic problems of funding to develop science projects. Thus, Mexico must increase its research efforts in nano-biology, nano-environmental-science, nano-medicine and toxicology.

Carbon nanotubes represent a very important material in N&N; with the rise of graphene, carbon nanotube research and, correspondingly, the number of publications directly related to this topic have generally decreased (Fig. 8). As in the case of N&N research, from a quantitative point of view, China and the USA are the leaders in carbon nanotube research. In Latin America, Brazil is the country with higher scientific production in this subject than Mexico. It is recommended that the enhancing the quality of papers that are published will improve the state of research in Mexico. Mexico has produced excellent papers on this topic and has been considered one of the regional leaders, but recently, the number of CNT papers published has progressively decreased. Mexico must recover its previous rhythm of paper production by carrying out research in fields such as nanomedicine, nanobiotechnology, nanotoxicology and environmental science (pollution, ecology, etc.). In particular, the application of carbon nanotubes for cancer (or another terminal sickness) treatments is a strong subject for developing interesting and successful projects based on the trends exhibited by the CNT field.

Acknowledgments

The author is grateful for grants CB-2008-SEP-107082 and CB-2008-SEP-106942 from CONACYT and to Dr. Florentino López-Urías for critical reading of manuscript.

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