Worldwide scientific research on nanotechnology: a bibliometric analysis of tendencies, funding and challenges.

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Abstract

The main objective of this study was to analyses the scientific trends in global research on nanotechnology, integrating scientific production, funding of studies, collaborations between countries and the most cited publications. The source for obtaining the research papers for our analysis was the Science Citation Index Expanded from the Web of Science. A total of 3,546 documents were retrieved during the period 1997-2018. The papers were published in journals in various areas, such as Food Science & Technology, Chemistry (Applied and Analytical), Spectroscopy and Agriculture. The co-word analysis showed the relationships between “nanoparticles”, which is the central word, and “silver nanoparticles”, “delivery systems” and “zinc-nanoparticles”. Scientific production was led by China (1089 papers), followed by the United States (523), Iran (427) and India (359). The main cited topics deal with the biomedical applications of nanoparticles, its synthesis from plants and its applications in food science.

Key words: Scientific research; nanotechnology; nanomaterials; international collaboration; journals; hot papers.

Introduction

Nanotechnology is a fast-evolving discipline that already produces outstanding basic knowledge and industrial applications for the benefit of society. Whereas the first applications of nanotechnology have been developed mainly in material sciences, applications in agriculture and food sectors are still emerging. Due to a rapid population growth, there is a need to produce food and beverage in a more efficient, safe and sustainable way. Here nanotechnology is a promising way to improve crop production, water quality, nutrition, packaging, and food security (Ranjan et al., 2016).

The national Nanotechnology Initiative Programme (2014) defines nanotechnology as the understanding and control of matter at dimensions between approximately 1 and 100 nm, where unique phenomena enable novel applications. Nanomaterials contribute to maintaining food safety by preventing the attachment of pathogenic and spoilage microbes onto food related surfaces, modulating cellular transport processes, and destroying existing microorganisms (Bata-Vidács et al., 2013).

Another contribution of nanotechnology is in the design of nanosensors to detect and identify food spoilage microorganisms, food pathogens, and their toxins (Doyle, 2006; Duran and Marcato, 2013). One on the largest and most accepted uses of nanosensors technology is its application in food packaging (Chaudhry et al., 2010). Nanomaterials in the form of polymer nanocomposites employed in food packaging are one of the latest methods for the control of pathogenic microbes (Duncan, 2011).

Nanomaterials are ubiquitous in industry and the consumer sector. Inorganic nanomaterials including transition metals and metal oxides/nitrides/sulphides/selenides are increasingly being used. Examples include titanium dioxide as a whitening agent (Chen et al., 2015a), silver nanoparticles as antimicrobial agents or catalysts (Waterhouse at al., 2004), nickel oxide as a cocatalyst (Chen et al., 2015b) zinc oxide for UV sensing platforms (Allen et al., 2011), iron nanoparticles embedded in silicon dioxide for magnetic sensing (Leveneur et al., 2011), aluminium oxide for sorption and optical sensing elements (Waterhouse et al., 2015) or gold nanoparticles for textile coloration or h2 production from biofuels

(Murdoch et al., 2011). Examples of successful applications include smart sensing chips or nano(bio)sensors for food safety analysis, point-of-care diagnostics, nanobacades for food authenticity, antimicrobial agents for food packaging, handling tools or contact materials, nano TiO2 coating for photocatalytic sterilization of products surfaces or drinking water, and nanoporous sorbent/catalysts for water purification via removal of contaminants like pesticides, viruses and bacteria (Chaudhry et al., 2010; Sharme et al., 2013; Yabutani et al., 2014).

Since nanomaterial and nanotechnology were put forward, they have been the focuses of scientific field, both within and across disciplines. Arguably due to the continual research funding and scientific breakthroughs for nanometer domain, new NNs promote the development of areas such as chemistry (Suominen et al., 2016) and materials science, medicine and pharmacology (Sahoo et al., 2007), electronics and photonics, environment and energy (Celik et al., 2017). Moreover, NNs also play a vital role in contributing to wastewater treatment because of their hight surface area and high reactivity (Xiao et al., 2009; Crane and Scott, 2012).

Bibliometric studies in science and technology are commonly used to improve the understanding of the research activity on a particular area of research or topic. These studies make use of bibliographic and scientific databases to find and focus on the main issues as well as the most prominent research developments. Additionally, it identifies collaboration networks concerning leading research groups and leading countries. In the case of nanotechnology, this will be the first study covering the complete spectrum of scientific research in this subject matter.

The main aim of this work is therefore to perform and evaluate a full bibliometric study on the nanotechnology research, using the research papers included in one of the most important scientific database. Moreover, this bibliometric study can extend the current and strong discussion around the potential use of nanotechnology and nanomaterials. The scientific impact of the research will also be stated and discussed.

Methods

The key words “nanotechnolog* and a set of key words related to nanomaterials were included in the search strategy in Science Citation Index Expanded (SCIE) included in the Web of Science Core Collection database (WOS) platform from Clarivate Analytics. These key words were, in addition to nanomaterial*”, the following: “nanoparticle*”, “nanofiber*”, “nanostructure*”, “nanosilver”, “nanopurification”, “nanoselection”, “nanocrystal*”, “nanocomposite*”, “nano-carrier*”. The asterisk at the end of a key word was used to retrieve variants of the term (e.g., plurals or adjectival forms, as “nanotechnological”). These selected key words were searched in the title field option of the registries to ensure a larger accuracy in the records found. Moreover, the search was restricted to the type of work “articles” and “reviews”. Editorial material, letters, bibliographical articles, reprints, book reviews and abstract of conferences were consequently excluded. The year’s scope was from 1997 to 2018.

The following indicators of production and scientific impact were obtained: evolution of the number of published papers funded and unfunded; journals that published a greater number of articles, citations, 5-year impact factor and quartile; subject categories (thematic areas) in which the most frequent journals are classified and most frequent key words in each subject category; most productive institutions and countries; highly cited papers and number of citations.

For the analysis of scientific collaboration, the index of signatures per paper of authors, institutions and countries was calculated. The index of collaboration between authors is the result of dividing the total number of authors signing the papers by the total number of papers. The index of collaboration between institutions and countries is calculated in the same way as in the previous case that is, dividing the total number of institutions or signatory countries in the works by the total number of works. This indicator is complemented by a world map of worldwide collaboration in which countries are linked by lines whose thickness is proportional to the number of works published in collaboration.

A social network analyses was carried out to identify the main institutions and organizations leading the research in this area. Although the previous indicators already offer a perspective of the topics dealt with, this was complemented with a network of co-words. Co-words analysis, based on social network analysis techniques, makes it possible to analyze research topics and their semantic interactions in order to determine the conceptual fronts of research in a specific field, through the co-occurrence of key words in the same document. This was visualized using the software Pajek and VOSViewer (Batagelj), applying a threshold of almost two papers written in collaboration. This threshold or minimum of papers is required to visualize properly the network. Analogous methodologies have been described to relate the topics of research in several fields such as probiotics (Aleixandre-Tudó et al., 2019), environmental science (Ho et al., 2007), tsunamis (Chiu, 2007) and deforestation (Aleixandre-Benavent., 2018), among others. Impact factor numbers were extracted from the 2018 edition of the Journal Citation Reports.

Results

1. General data and journals of publication

During the two decades analyzed (1997-2018), 3,546 works were published and included in SCIE. Ninety-three percent of the papers were published in the last decade (2009-2018) and almost three quarters (72%) in the five-year period 2014-2018. Figure 1 shows the evolution of published works and citations in the decade 2009-2018.

The number of funded and not funded articles published during the 2009-2018 period is shown in Figure 2. As can be seen, the number of papers funded also increased progressively over the last decade, from 43 in 2009 (61.4% of papers published that year) to 487 in 2018 (78.2%). The overall percentage of articles funded in the decade was 70.6%. Papers in this decade received 52,595 citations, of which 41,088 (78.12%) corresponded to funded papers and 11,507 (21.88%) to not-funded papers. The average number of citations per article in the entire period was 15.43 (Figure 3). In global figures, the funded works, which represent 73.4% of the total works, received 78.12% of the citations, while the non-funded works, which represent 21.88% of the published works, received 26.6% of the citations. In short, funded papers received 4.7% more citations than non-funded papers.

The papers were published in 340 different journals. The 16 journals with more than 30 papers are presented in Table 1, together with the country of publication, number of citations received, citations per article, 5-year impact factor, thematic categories and quartile. The journal *Analytical Methods* stands out with 685 papers, followed by 5 journals with more than 100 papers: *Journal of Agricultural and Food Chemistry* (239), *Food Chemistry* (188), *Food Hydrocolloids* (139) and *Bioresource Technology* (127). Seven of the 16 journals were published in the United Kingdom, four in the United States, and three in the Netherlands. The journals that received the highest number of citations were also *Analytical Methods* (6,800), *Journal of Agricultural and Food Chemistry* (6,767), *Food Chemistry* (5,230). Those with the highest ratio citations per paper were *Biotechnology Progress* (79,03), followed by *Journal of Food Engineering* (32,17), *Bioresource Technology* (30,97) and *Journal of Agricultural and Food Chemistry* (28,31). Journals with higher 5-years impact factor were *Bioresource Technology* (6.589), *Food Hydrocolloids* (6.103), *Food Chemistry* (5.488) and *Food Research International* (4.437). All these journals were classified in the first or second quartile of the Journal Citation Reports: eleven journals in the first quartile and five in the second quartile.

2. Subject categories and topics of research

Table 2 presents the subject areas of the journals in which the articles were published, as well as the most frequently used keywords and the journals with the most articles in each area. The area that included most papers was Food Science & Technology (2,675) and the most frequent key words in this area were “Nanoparticles” (591), “Silver nanoparticles” (278) and “Gold nanoparticles” (264). The three most productive journals in this area were *Analytical Methods* (696 papers), *Journal of Agricultural and Food Chemistry* (253) and *Food Chemistry* (191). The second most productive area was Chemistry, Applied (725), with “Nanoparticles” (220), “Stability” (108) and “Delivery systems” (101) as the most frequent key words. In this area highlights the following journals: *Journal of Agricultural and Food Chemistry* (253), *Food Chemistry* (191) and *Food Hydrocolloids* (145). The third area with a similar number of papers that the previous one was Chemistry, Analytical (724), with the key words “Liquid-chromatography” (119), “Sensors” (117) and “Gold nanoparticles” (110) and the most prolific journals being *Analytical Methods* (696), Journal of AOAC International (18) and *Phytochemical Analysis* (4). Other areas that highlights with more than 200 papers were Spectroscopy, Agriculture (Multidisciplinary), Plant Sciences, "Biotechnology & Applied Microbiology, Nutrition & Dietetics and Agricultural Engineering.

The network of cowords generated from the published works (Figure 4) provides a complementary view of the topics covered, since shows the relationships established between the keywords that have been mentioned together in the same works. The central word in the network is “Nanoparticles” and shows the strongest associations with “Drug Delivery Systems” (in 247 `papers), “Silver Nanoparticles” (in 146), “Zinc nanoparticles” (in 115), “Antibacterial activity” (100) and “Titanium dioxide nanoparticles” (in 97). Other relevant relationships were between “Antibacterial activity” and “Silver Nanoparticles” (159); between “Silver Nanoparticles” and “Gold Nanoparticles” (122); and between “Drug Delivery Systems” and “Stability” (111) and “Chitosan nanoparticles” (117).

3. Institutions and countries of publication

Table 3 shows the 27 institutions with 20 or more published papers. Most productive institutions were Islamic Azad University (Iran) (76), followed by Chinese Academy of Sciences (China) (69), Jiangnan University (China) (64) and University of Massachusetts System (United States) (62). China highligths with 12 institutions, followed by Iran with 5 institutions. By number of citations six institutions highlight with more than 1000 citations: University of Massachusetts System (1950), Spanish National Research Council-CSIC (1384), Chinese Academy of Sciences (1263), United States Department of Agriculture, USDA (1160), Jiangnan University (1096) and Islamic Azad University (1084). The institutions that obtain the highest percentages of financing are the Chinese, which in some of them reach 100% (Southwest University, Hunan University and Chinese Academy of Agricultural Sciences). At the opposite extreme, i.e. with a lower percentage of funded work, are some institutions in Iran (Islamic Azad University, Tarbiat Modares University, University of Tehran and Isfahan University of Technology), Brasil (Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA) and China (Qingdao Agricultural University).

Scientific production by country is led by China (1080), followed by the United States (523), Iran (427), India (359), South Korea (185), Brazil (127) and Spain (108), all of which have published more than one hundred papers. Next are 12 countries that published between 50 and 100 works: Japan (95), Italy (93), Canada (87), Germany (83), United Kingdom (79), Taiwan (72), Egypt (72), Poland (68), Turkey (62), Australia (57), Mexico (54) and Portugal (51).

4. Patterns of collaboration

The evolution of the rate of collaboration of authors, institutions and countries is shown in Figure 5 depending on whether the papers were funded or not. As can be seen, the overall index of collaboration between authors for the period 2009-2018 was 4.62 authors per paper and has increased by one point from 2009 (4.4) to 2019 (5.4). The index was higher for funded papers (5) than for not-funded papers (3.8). The index of collaboration between institutions was also higher for funded papers (2.2) than for not-funded papers (1.8), while the index of collaboration between countries hardly changed and was around 1.2.

Collaboration between countries is reflected in the world map in Figure 6. The most prominent was the collaboration between the United States and China (in 120 articles), followed by the United States with India (28) and South Korea (25). China also published articles in collaboration with Australia (22), Canada (17) and Singapore, and India with South Korea (16). Other collaborations included Denmark and Poland (15) and the United States and Saudi Arabia (15).

5. Highly cited papers

Table 4 lists the references and number of citations of 19 papers that were cited more than 200 times. The most cited paper, entitled “Medical application of functionalized magnetic nanoparticles” was published in 2005 in *Journal of Bioscience and Bioengineering* by Ito et al, a team from Department of Biotechnology, School of Engineering, Nagoya University, Japan. This paper received 958 citations. The paper with the second highest number of citations (905), was published in *Biotechnology Progress* in 2006 by Chandran et al, from Nanoscience Group at the National Chemical Laboratory in Pune, India. In this paper, the authors discourse about the synthesis of gold nanotriangles and silver nanoparticles using Aloe vera plant extract. The following are two papers with about 500 citations published in the journals

Biotechnology Progress and *Food Additives and Contaminants Part A-chemistry Analysis Control Exposure& Risk Assessment*. The first of these, published in 2003 by the above-mentioned team in Pune, India, was entitled “Geranium leaf assisted biosynthesis of silver nanoparticles”. The second published in 2008 was entitled “Applications and implications of nanotechnologies for the food sector” and was carried out by a team from Defra Central Science Laboratory in York, United Kingdom.

Discussion

This work has made it possible to improve knowledge on topics, trends and sources used to disseminate nanotechnology research, as well as to obtain a map of global research on this topic and its impact. SCIE from Web of Science Core Collection was used as a data source because it is the database commonly explored in this type of studies due to its multidisciplinary character and because it offers the necessary data and indicators to know the citation and impact of the works. To reach comprehensive results, for the search strategy we used the terms and the experience reported in previous works (Porter et al., 2008).

According to Duran et al., (2019), the first bibliometric studies in the field of nanotechnology date back to 1997 and already showed that it was an emerging area of research (Braun et al., 1997). Subsequently, several studies have shown that this is a constant trend (Glanzel et al., 2003; Hullmann et al., 2003; Schummer, 2004; Arora et al., 2014; Munoz-Sandoval, 2014).

Nanotechnology is a very recent area of research, as demonstrated by the fact that three quarters of the work has been published in the five-year period from 2014 to 2018. The exponential growth of publications has also been described in other works (Roco et al., 2011; Pardo-Guerra, 2011; Youtie et al., 2018). In accordance with the growth in the number of published papers, the number and percentage of funded works has also increased. These papers increased by almost 17 percentage points over the decade 2009-2018, which may be an indication of the significance that this topic arouses among funding institutions. The overall percentage of funded articles in our work was 70.6%, a higher percentage compared to what was found in other areas such as probiotics where it was 64% (Aleixandre-Tudó et al., 2019).

A wide spectrum of different institutions involved in nanotechnology research and applications has been identified, with universities and research centres predominating. In analysing the scientific output of institutions we must remember that some of them, such as the French National Center for Scientific Research (CNRS), the Spanish National Research Council (CSIC) and the Chinese Academy of Sciences, group together many different research institutes and research laboratories, which means that they cannot be compared at the same level as other individual smaller universities. Moreover, these institutions often publish jointly with universities and other public or private research organizations (Yamashita and Okubo, 2006]. Therefore, the list of institutions should be interpreted with caution when interpreting the performance of the institutions.

As we have seen, twelve of the 27 institutions with more than 20 papers were Chinese and five were from Iran. These results coincide in part with other works (Guan and Ma, 2007; Niu and Qiu, 2014; Tang et al., 2015; Jiang et al., 2018). In the study of Jiang et al. (2018), the ranking of institutions in the two decades analysed (1997-2016) was headed by three Chinese institutions: Chinese Academy of Science, Tongji University and Harbin Institute of Technology, followed by the Islamic Azad University (Iran), which in our work has been the most productive institution, and National University of Singapore, which in our study was in ninth position. A previous study also explained the striking development of nanoscience and nanotechnology in Iran (Munoz-Sandoval, 2014).

In relation to the countries scientific production, one of the most striking results of our work is that China is the first country in publishing papers, doubling even the second country, the United States. Another striking result is the production of a number of emerging countries that do not usually appear in the rankings of other areas or subjects, such as Iran, which is in third place, India, which is in fourth, and then South Korea and Brazil. These results are similar to those of Youtie et al. (2018), in whose work one of the main conclusions was the emergence of China. In the work of Jiang et al. (2018), the ranking of countries in the two decades analysed (1997-2016) was headed by China, followed by the USA, Iran, India, South Korea and Spain. The rapid growth of nanotechnology research in China is due, on the one hand, to increase funding and, on the other, to the boost the Chinese government is giving to publication in SCI-indexed journals (Brahic, 2005; Bai, 2005; Bai and Wang, 2007). As far as Europe is concerned, research in nanotechnology was not very intense before 2000, although in several countries, such as the United Kingdom, Sweden and Austria, universities had already started to advance in the 1990s (Schummer, 2007). Since 2000, governments of other European countries began to give support and to create research institutes and to promote research in nanotechnology in universities (Schummer, 2007), considering it as a priority area, which already was being done in other countries like USA and Japan (Terekhov, 2017).

In order to obtain detailed information on nanotechnology research, we investigated the structure of the network of cowords in the papers. From this analysis, the implications of research in nanotechnology in the field of food science and technology, chemistry, nutrition, agriculture and biotechnology and applied microbiology can be deduced. The analysis also presents opportunities to identify and manage the risks associated with nanotechnology research, development and applications and highlights the difficulties in managing the risks. The coword network has shown the strong connection between the central term "nanoparticles" and other key words, such as "Drug Delivery Systems", "Silver nanoparticles", "Antibacterial Activity". "Drug Delivery Systems" refers to systems for transporting pharmaceutical compounds in the body based on nanoparticles to safely achieve a desired therapeutic effect. These systems are proving essential for the treatment of chronic diseases.

Scientific collaboration plays a key role, along with competition, in the advancement of science in any country. Collaboration enables the exchange of knowledge, experience and the sharing of resources, thus achieving greater efficiency that benefits society (Lee and Bozeman 2005; Wang et al., 2014). On the other hand, it has been reported that there is a positive correlation between scientific output and impact and international collaboration (Schummer, 2004; Lee and Bozeman 2005; McFadyen and Cannella 2004; He et al., 2009; Wuchty et al., 2007). Scientific collaboration in the field of nanotechnology has been very relevant, as 83% of the articles were published by two or more authors. International collaboration is an important dimension of nanotechnology. Authors from the UK, France and Germany show the highest degree of international co-authorship while those from Iran and

China are at the other extreme (Terekhov, 2017). However, China has increased its collaborative publishing, especially in the international context, having established collaborations with over 150 countries in recent decades (Niu and Qiu 2014; Zhou and Glänzel 2010).

Concluding remarks

Nanotechnology is a rapidly growing area of research worldwide, with a high annual growth rate. The geopolitical landscape related to nanotechnology has changed dramatically and the focus of nanotechnology research (in terms of scientific publication output) has moved to Asia, with China, Iran and India leading the way. Nanotechnology has great potential for future development in a wide range of areas. The increasing number of funded papers is an indicator of the interest that this topic arouses among financing institutions. Nanotechnology research is expected to accelerate in the coming years and to lead to new applications to meet society's needs in various fields, such as energy, agriculture, environment, biotechnology and health, among others. This research is expected to lead to the emergence of new nanomaterials and nanosystems (Roco et al., 2011; Suominen et al., 2016).

Limitations and future research

A possible limitation of this study may have occurred due to the loss of relevant documents not recovered in the searches, since there is not yet a completely standardized terminology and some researchers add the prefix "nano" to new discoveries and materials related to nanotechnology (Takeda et al., 2009). According to some studies, in the early 1990s only about 20% of articles used terms with "nano" prefixes in their titles and abstracts, while today the terms are more standardized and 80% of articles carry this prefix in their titles and abstracts (Porter et al., 2008; Arora et al., 2014; Youtie et al., 2018). This problem is also discussed in a previous work (Hullmann and Meyer, 2003) in which they also used the root "nano" as a search word, indicating that this is a useful approach when the field is interdisciplinary and difficult to define, and that often experts in the field do not agree on the precise nature of nanotechnology. In our case, the search strategy was based on several previous studies (Glanzel et al., 2003; Schummer, 2004; Guan and Ma, 2007).

Future research in this field could analyse global research developments, the consequences of funding, the social impact of research, the cooperation between countries and the emergence of new generations of nanomaterials and nanostructures.

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