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RESEARCH PAPER

Twelve years of nanoscience and nanotechnology publications in Mexico

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Abstract Mexico is the second country in Latin America with regard to Nanoscience and Nanotechnology Research and Development, according to various indicators. Nanoscience and Nanotechnologies are viewed as strategic areas in government policy since 2001. In the last few decades, important policy changes in Science and Technology (S&T) have been implemented with an aim to integrate the business sector with government scientific research. This article reviews information from the Web of Science relevant to articles on nanoscience and nanotechnology stretching back 12 years, and explains the changes in S&T policy. The information uncovered leads to three conclusions: the participation of the business sector is negligible; there is a significant concentration of scientific production among a very few institutions; and the country is essentially divided geographically, with scientific production concentrated in the center and north of the country.

Keywords Nanotechnology · Nanoscience · Bibliometrics · Mexico · Science and Technology

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Introduction

Nanotechnology is the manipulation of matter at the nanometric scale. At this scale, matter exhibits chemical, physical, and biological properties different from the same matter at a larger (bulk) scale. As a general rule, nanotechnology implies working with matter between 1 and 100 nm in size; however, the potentials of nanotechnology can still be exploited at a larger scale. Typically, manufacturing—with nanotechnology's enabling power—creates products that are more resistant, more effective, and with new characteristics which has captivated the research and production chains of various countries. The United States (USA) launched its National Nanotechnology Initiative in 2000, with various nations following that example and with their own programs to advance this revolutionary technology. Developing countries, particularly those in Latin America, are grounding their expectations of improved productivity and competitiveness on the application of emergent technologies, including nanotechnology. Mexico is the second country in Latin America in the Research and Development (R&D) of nanoscience and nanotechnology (N&N) according to various Science and Technology (S&T) indicators (Robles-Belmont and Vinck 2011; Kay and Shapira 2009; OICTeI 2008). N&N have been viewed as strategic areas in government policy in this country since 2001.

From the 1980s Mexico began to modify its policy and S&T structure with the aim of integrating R&D with the business sector and the government. By the end of the 1990s, the country had made significant changes to its academic and research infrastructures to increase the competitiveness of its emerging knowledge economy platform (OCDE 1994). N&N are priority areas within this platform. In order to assess the impact of these adjustments to N&N research in Mexico, we reviewed the evolution of S&T policy and followed the scientific publication record of the subject from 2000 until 2012. This allowed us to uncover important trends that illustrate three aspects of N&N innovation in Mexico: (1) There is very little, if any, private sector participation in scientific publications, which raises the question of N&N innovation driven by the business sector, as the S&T policy intended; (2) the researched literature is concentrated in a few universities and research centers, which led to a considerable inequality among teaching and research institutions; and (3) geographically speaking, there are two Mexicos, in terms of R&D. The central and northern zones are the source of a significant number of publications and institutions, while the southern zone is practically unrepresented, which reinforces the geographic knowledge and scientific resource gap among states in the country.

Methodology

Data on the evolution of Mexican S&T policy were obtained from several published governmental plans and from specialized literature and the data on scientific publications were obtained from ISI Web of Science (WOS), using the query terms provided in Kostoff et al. (2006). All available citation databases (SCI-Expanded, SSCI, AHCI, CPCI-S, and CPCI-SSH) and publication languages were included. For the period January 1, 2000 to December 31, 2012 4,471 articles were published with at least one author with an institutional affiliation in Mexico at the time the article was published. Institutions include public and private universities, research centers, government agencies, and firms. Of these articles, roughly half (53 %) were by authors only in Mexico and the remaining papers (47 %) had at least one author with a foreign institutional affiliation. It is worth mentioning that since many of the articles authors' institutional affiliations are associated with a sub-site located in a different city and/or state from the main headquarters for that institution, a manual procedure was conducted to cluster all the departments, research centers, and campuses of the same institution regardless of the geographic location. In situations where complete information was not provided, each individual paper was referenced to update the information provided by ISI WOS.

Obtaining this sort of data is not something new. For instance, Robles-Belmont and Vinck (2011) provides a comparison of the results of five existing bibliometric search strategies for the 1990–2008 timeframe and an analysis of Mexico's publication trends based on the merged results. The results ranged from a high of 9,650 articles (Mogoutov and Kahane 2007) to a low of 1,555 using the nano* query, with the combined strategy producing a result of 11,757 articles for 18 year span. The results of the Kostoff et al. query used in this paper for the same timeframe provides a total of 4,471 articles, putting this estimate near the median value of the five existing queries. Despite the lower number of overall publications, the Kostoff et al. query was chosen because the resulting trends from an institutional perspective were similar to those found in these recent studies and the search terms were publicly available. Furthermore, the objective of this research was to analyze the institutional and geographic distribution of nano-related research activity within Mexico in light of S&T policy objectives rather than measuring the publication output of Mexico with other countries.

The nanotechnology development context in Mexico

Mexico has 113 million residents, of which 53.3 million are poor, according to government figures (Coneval 2013). Furthermore, it is estimated that another 34.8 % of the Mexican population is vulnerable, and likely to become poor if any of the other socioeconomic variables (health, education, and employment) is disturbed (Coneval 2013). Fitting to the knowledge economy paradigm, the development of S&T is considered a key instrument for raising international competitiveness and social development; this is the paradigm that Mexico has adopted for the past two decades through a restructuring of its higher education system and R&D programs (OECD 1994).

Despite the fact that the government has only applied about 0.4 % of the nation's GDP to R&D in recent years, putting it in the last place among countries of the Organization for Economic Co-operation Development (OECD), of which it has been a member since 1994 (González Amador 2009), the changes made to the structure of teaching and research have resulted in a considerable number of scientific publications (Luna-Morales 2012)[1]; with references to N&N in those publications far from an exception.

The R&D of N&N in Mexico occurs in a context notable for the governmental push toward integrating businesses with academia and research, one of the key axes of the knowledge economy paradigm. This process was well underway in Mexico since before the knowledge economy paradigm became a policy recommended by the World Bank (WB) and the OECD at the beginning of the 1990s, but it was notably accelerated with Mexico's incorporation into the OECD in 1994.

The 1982 economic crisis provided justification for a change in the State-directed development policy. The government of President Miguel de la Madrid (1982–1988) decided that S&T should be guided by market mechanisms; that is, be aligned with market demands and oriented toward the production priorities of business. During the subsequent government of President Carlos Salinas de Gortari (1988–1994), economic liberalization, financial deregulation, and mass privatization of state enterprises and the signing of the North American Free Trade Agreement shaped S&T policy. In 1991, for example, the Promotion and Protection of Industrial Property Law was introduced to protect processes, products, and developments of foreign business operating on Mexican territory with the same requirements as national businesses (Rocha and López 2003, p. 114). Also the Science and Technological Modernization Program was created to assist in the generation of technological activities and to promote competitiveness of private business, seen as a key sector in the drive for development in advanced countries and a strategy worth copying (María y Campos 2002, p. 38). This program awarded credit to businesses or research centers that innovated or developed new technologies, and marked the beginning of the move toward the privatization of scientific knowledge and technological development in public institutions.

Under the administration of President Ernesto Zedillo (1994–2000), there were changes to programs but the tendency to link the private sector to the development of S&T continued. In 1994, Mexico became a member of the OCED and requested an external evaluation of its scientific-technological system. The OECD recommended various measures to create a technologically competitive industry, among them are: the creation of a single institution to control all of S&T, the creation of a policy in S&T linking business sector needs, the search for external financing, and the restructuring of the Science and Technology National Council (CONACYT) (OECD 1994). To reconcile S&T policy with the OECD recommendations, Mexico sought, in 1997, $700-million from the WB to finance scientific and technological research, link universities with the business sector, restructure public research centers, and improve private-sector technologies (World Bank 1998). The National Autonomous University of Mexico (UNAM), for its part, obtained more than $230-millones in financial support from the Inter-American Development Bank in 1994–1996 (Maldonado–Maldonado and Rodríguez-Sabiote 2000), an indication of the independence of the top educational institution with respect to government policy.

During President Vicente Fox's term in office (2000–2006) the remaining regulatory recommendations of the OECD were fulfilled, with the exception of those that had to do with public financing of research and development (R&D) that had not yet reached the goal of 1 % of GDP.

N&N appeared for the first time as a strategic area to pursue in the *Special Program of Science &*

[1] Luna-Morales writes about scientific publications and refers to Coll azo-Reyes: "The accumulated number of published papers had reached the 8000 mark by the late 1970s, a figure equivalent to the number of articles published annually in mainstream journals in recent years by Mexican researchers" (Luna-Morales 2012, p. 736).

Technology 2001–2006 (PECyT), which was part of the *National Development Plan 2001–2006*, which presented for the first time in Mexico a far-reaching state policy for S&T, oriented toward supporting S&T education and fomenting public and private investment in R&D. The orientation toward stimulating private research, to integrate the business sector in the state's S&T project and to prioritize physical/chemical sciences and engineering, is explicit throughout the Special Program.

Also for the first time in official scientific policy documents, nanotechnologies are mentioned in the 2001 PECyT as a strategic area in advanced materials development. In the PECyT the areas of interest for development were outlined (catalysts, polymers, nano-structured materials, thin film, semiconductors, metallurgy, biomaterials, optical materials, advanced ceramics, and the creation of materials and processes), and a brief summary was provided of those research centers that could undertake development work in this area, noting the human resources available and the industrial cooperation potential.

The PECyT also highlighted the necessity for a National Nanotechnology Program to sustain a network of scientific exchange in this area (CONACYT 2002). By the end of 2009, the Nanoscience and Nanotechnology Network (RNyN) was formed—yet the National Nanotechnology Program still had not been created. The *National Development Plan 2001–2006* also viewed N&N as a strategic sector for intensive development.

At the time, the *Special Program of Science, Technology and Innovation 2008–2012* established N&N as one of the nine priority areas for S&T development. By the end of 2010, the implementation of the N&N policy in Mexico took form in the creation of four significant developments: the creation of a national research network (RNyN); the previously mentioned construction of two national laboratories; the development of technological parks; and the establishment of the Bi-national Sustainability Laboratory.

The RNyN network was created with a budget of more than $700-thousand. It brings together more than 130 researchers from various universities and research centers throughout the country (CONACYT 2013).

The National Nanotechnology Laboratory (NaNoTeCH) at the Advanced Materials Research Center (CIMAV) in Chihuahua was constructed in 2006. The Potosí Institute of Scientific and Technological Research (IPICYT) built the National Laboratory for Nanoscience and Nanotechnology Research (LINAN). Both national laboratories received a budget of approximately $2-million for their construction and equipment (CONACYT 2006). These labs are leased to the interested parties.

Several industrial parks were created in the first decade of the twenty-first century. The Research and Technological Innovation Park (PIIT) located in the city of Monterrey represents a $100-million investment for the physical plant with another $150-million for equipment; moreover, it hosts two specialized incubators in emerging technologies: one for biotechnology and the other for nanotechnology. It is also the headquarters of the Nanotechnology Cluster of Nuevo León (CNNL), which is the signature project of the PIIT (Záyago Lau 2011).

The Bi-national Sustainability Laboratory (BNSL) created in the border states of Chihuahua (Mexico) and New Mexico (USA) on New Mexico territory was conceived within the framework of the SPPNA (Security and Prosperity Partnership Program for enhanced North American competitiveness) agreement to provide security to the border zone through the cultivation of high-technology industries and the economic development of the region.[2] The BNSL received initial support of $400-million from the US Economic Development Administration of the Department of Commerce, another equal amount from Mexico's CONACYT, and $100-million from the Department of Economic Development, State of New Mexico (Acosta 2006b; Sandia National Laboratories 2005). It is worth pointing out that the BNSL is not a research lab per se, but a business laboratory with the aim of bridging institutions and universities with productive and commercial activities. Although no official figures exist on the total funding allocated to N&N research in Mexico, some authors estimate that

[2] "The recent [March 2006] meeting of President Bush, Mexican President Vicente Fox and Canadian Prime Minister Stephen Harper in Cancun underscores the importance of establishing and maintaining strong economic collaborations among the NAFTA partners to fulfill the Security and Prosperity Partnership program for enhanced North American competitiveness. We expect the BNSL to provide a unique and important mechanism for achieving the economic goals of our governments and the aspirations of their citizens in the border region" (Acosta 2006a).

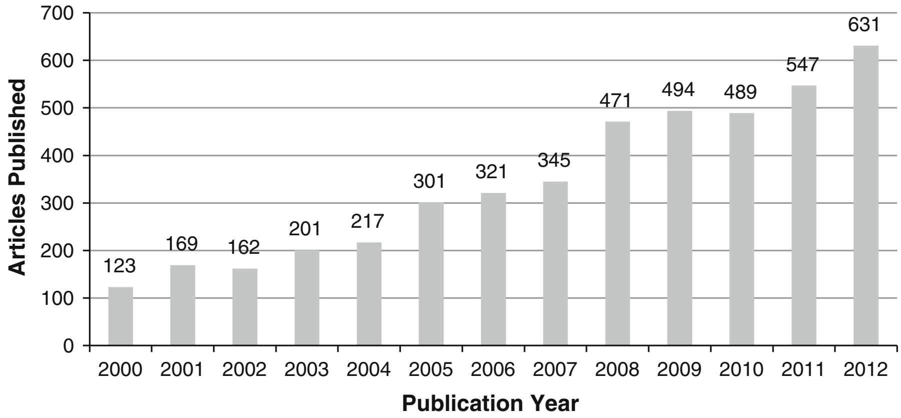

Fig. 1 Evolution of N&N scientific publications by Mexican authors (2000–2012). *Source* Own research (2013)

the Mexican government has invested, between 1998 and 2004, $14.4-million (CIMAV 2008); or $60-million between 2005 and 2010 (Takeuchi and Mora Ramos 2011). Other authors have identified more than 100 businesses commercializing, producing, or with R&D activities in nanotechnology by 2011 (Záyago et al. 2012).

An optimistic reading of the S&T policy changes in Mexico and the driving of N&N would lead one to think that there is at least an incipient integration between business and research. Public funding programs were re-oriented toward partnerships with the private sector. Also, given the emphasis on regional autonomy in issues of S&T through funding schemes such as the so-called "mixed funds" administered by the states and applied to the multi-user laboratories, one might see development, although small-scale, in priority areas such as N&N throughout the country.

Mexican nanotechnology publications

Mexican scientists have been researching matter at the nanometric scale since the 1990s. The first publications that used the term "nano" by authors belonging to Mexican institutions is in 1995 (WOS), although this does not include the terms "ultrafine particles" most often used in the 1980s and 1990s. One study conducted by Cyted (Ibero-American Program of Science & Technology for Development) between 1999 and 2002, with the participation of seven Ibero-American countries (among them Mexico) worked on the topic of "Fabrication and Characterization of Nano Structures for Micro- and Optic-Electronics" (CYTED 2003). Our review of scientific articles on N&N found within the WOS from the year 2000 shows a consistent increase in scientific publications (Fig. 1).

The number of publications increased more than 5 times over that period of 12 years. The tendency is very similar to that identified by Robles-Belmont and Vinck (2011) for the period 2000–2007, although their count, performed with different keywords, found a greater number of articles. The period 2008–2012 shows an even higher and sustained level of publications.

In analyzing the institutional membership of the Mexican authors, the reduced participation of authors linked to private institutions becomes clear, as does the meager presence of authors tied to businesses (Fig. 2). If we look at the distribution within these sectors, we see that all the publications of private institutions originate in private universities. This may show that the participation of businesses is little or non-existent.

Note that half of these 139 publications are distributed across three private universities: ITESM (35),[3] Ibero (23),[4] and UPAEP (9).[5] There are less than 50 scientific articles published in those 12 years by the business sector. Although this is not a definitive indicator that private businesses do not conduct research, it at least shows that any research that is performed does not see the light of day in scientific

[3] Monterrey Institute of High Technology.

[4] Ibero-American University.

[5] Public Autonomous University of the State of Puebla.

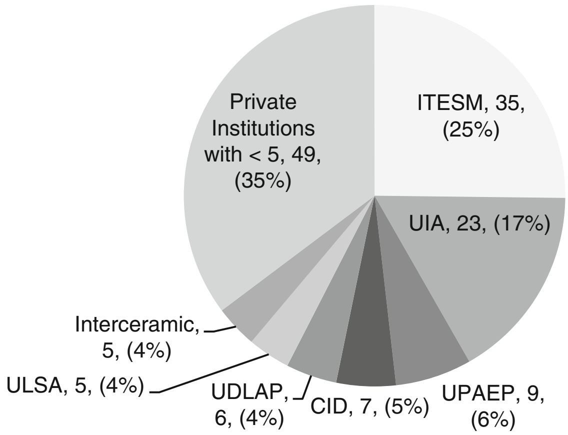

Fig. 2 N&N scientific publications of Mexican researchers in registered private institutions (2000–2012). *Source* Own research (2013)

publications; and it is most likely that they do not perform original research.[6] If we consider that in Europe half or fewer of businesses that innovate do not conduct research, but rather the innovation is the result of the purchase of technology, internal procedures, or other modalities (Catozzela and Vivarelli 2007), it is likely that in the Mexican case, where there is no tradition of innovation or research on the part of businesses, the data shown in this investigation are indicative of practically no research on the part of the business sector.

The next step in this study is to determine the degree of centralization of the scientific publications across public institutions, those in which the majority of the publications are concentrated (Fig. 3).

Note that a group of only three institutions, UNAM (1,706), CONACYT Centers (1,132), and IPN (1,061), account for 57 % of the total publications from public institutions. It is worth pointing out that many of these institutions have centers and sub-units in different parts of the country. For example, UNAM has research centers in Ensenada, Baja California; Cancún, Quintana Roo; León, Guanajuato; and a few others. The same is true of IPN and UAM (with different sub-units within the Distrito Federal). In the case of private universities, ITESM has various campuses throughout the country, but those that have published most on N&N material are located in the center-north of Mexico. This result occurs because several states in the country, without having local autonomous universities with a high number of publications, host sub-centers or research centers from universities with high publication records on N&N.

The spatial distribution of nanotechnology publications appears to show the inequality in the development among states in the country. According to the Human Development Index produced by the United Nationals Development Program (UNDP), the states in the center-north of the country have a very high level of development. For example, the DF, which accounts for the majority of nanotechnology publications (2,138 articles), has a level of development similar to the Czech Republic; while Chiapas (5 articles), with one of the lowest numbers of N&N publications, has a level of development equivalent to that of Mongolia (PNUD 2010). It is noteworthy, however, that exceptions exist. Such is the case of San Luís Potosí which has a low development level (similar to Saint Vincent and the Grenadines (PNUD 2010) but a high number of N&N publications (467 articles). This is explained by San Luís Potosí's hosting of the LINAN facility. On the list of high publication results for N&N, notable are the states of Querétaro (442), Puebla (388)—headquarters of the National Nanoelectronics Laboratory (LNN), Morelos (332)—headquarters of various UNAM research centers, Chihuaua (261)—headquarters of NaNoTeCh, and Nuevo León (216). In contrast, the states with very low numbers of N&N publications are Oaxaca (26), Veracruz (25), Campeche (6), and Guerrero (4). In general, the geo-spatial distribution of N&N publications in Mexico is a reflection of the inequality in infrastructure, economic performance, and development across the country (Fig. 4).

The Mexican government implemented policies in an attempt to reverse the tendency toward a concentration in scientific and technological capacity across a few states. CONACYT administers the National System of Researchers (SNI), created in 1984 by presidential decree, with the objective of promoting and strengthening research and innovation in the country. Those who aspire to the SNI are evaluated for their scientific production (articles, patents, and research) and, based on specific criteria, are ranked at a level which brings with it an economic stimulus.

[6] Some authors believe that the largest part of the public funding for R&D destined for businesses were in fact received by transnational corporations that do not conduct research in the country (Loyola Díaz and Paredes López 2009).

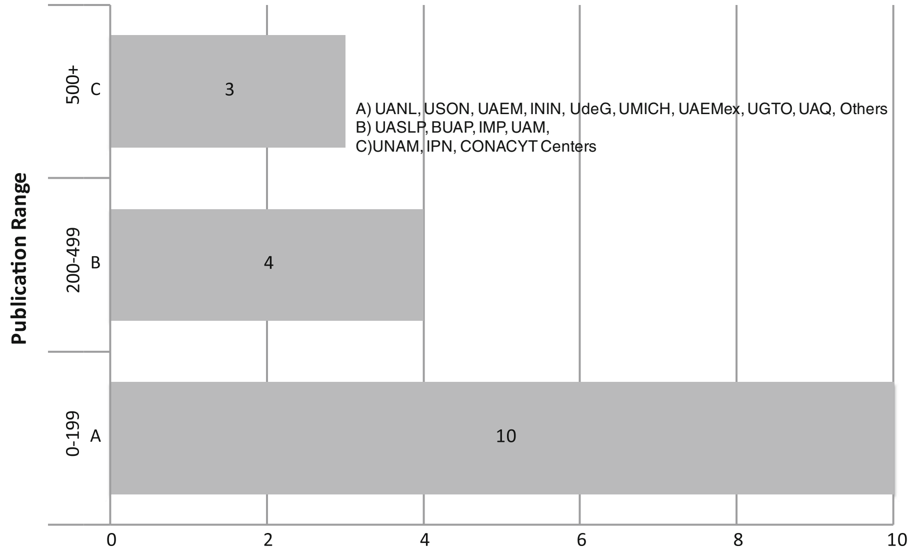

Fig. 3 Distribution of N&N scientific publications by Mexican researchers in public institutions (2000–2012). *Source* Own research (2013)

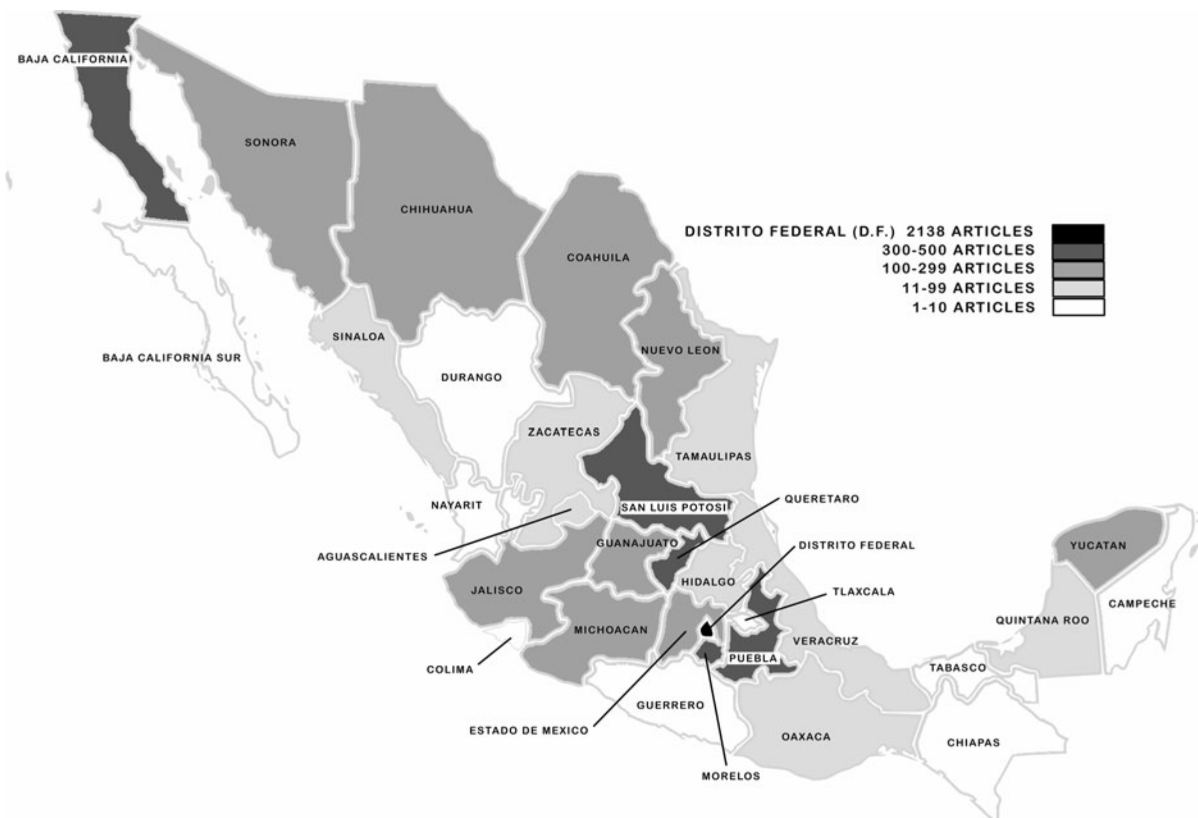

Fig. 4 Geographical distribution of N&N scientific publications in registered institutions by States in Mexico (2000–2012). *Source* Own research (2013)

Table 1 Number of projects supported by the Mixed Funds program

State	Number of projects	Areas
Nuevo Leon	19	New materials and products based on nanomaterials, coatings, nanoparticles, polymers, strengthening laboratories, research and education plans in nanotechnology
Baja California	6	Nanomaterials, nanotubes, and thin films for the electronics industry
Guanajuato, Hidalgo, Veracruz	3	Nanomaterials, nanoparticles, nanostructures
Coahuila, Morelos	2	Nanostructured materials, polymer/graphene nanocomposites
Chihuahua, Jalisco, Estado de México, Michoacán, Querétaro, Sonora, Yucatán	1	Micro- and nanostructures, nanomaterials, nanoparticles, coatings, surface micro- and nano-scopy, scientific infrastructure
Remaining states	0	–

Source Own research (2013)

With the aim of promoting the decentralization of research, CONACYT awards a larger stimulus to researchers or technologists who belong to universities or research centers outside the metropolitan areas (SNI-reglamento 2013). The creation of two nanotechnology national laboratories in the provinces resulted in an increase in the publications of those states. This illustrates some of the policy efforts to deconcentrate the scientific infrastructure.

With the same intent, CONACYT and the various states and some municipalities created the "Mixed Funds" (FM) program. This is a series of blind trusts that promote research in topic relevant to federal organizations and each state provides a financial support according to its economic capabilities. For the period 2001–2012, some \$583-million have been disbursed by the FM program. In total, the state of Nuevo León paid out \$82-million while Guerrero only provided \$3.8-million and Oaxaca, \$3-million.[7]

The FM program also had an impact on the development of N&N and perhaps on the pace of publications. For the period 2004–2010, the government of Nuevo León financed 19 nanotechnology projects (FM-Nuevo León 2013) while other states provided no project support in this area. In the same period, Baja California supported 6 projects; Guanajuato, Hidalgo and Veracruz financed 3 each; Coahuila and Morelos, 2; and Chihuahua, Jalisco, Estado de Mexico, Michoacán, Querétaro and Sonora, 1 each (Table 1).

[7] The majority of the 35 Mixed Funds incorporated (32 state and 3 municipal) were created in 2001, with the exception of the DF, which began in 2007.

Another indicator that illustrates the relevance of nanotechnology for the states are the grants provided to conduct studies abroad. Each state holds an annual convocation and identifies priority areas. As with the FM program, the foreign study grants are co-financed between the state and CONACYT. An examination of the 2013 Convocation for study abroad grants shows that the pattern of inequality and concentration in the promotion of nanotechnology is repeated here. For example, the state of Nuevo León awarded 200 grants for those interested in subjects pertaining to high technology, including nano. In contrast, Veracruz offered 50 grants; Tlaxcala 10; and other states such as Oaxaca, Guerrero, and Zacatecas with 20, 10, and 8 spaces, respectively, none of which were aimed to nanotechnologists. This reinforces the consistent tendency toward a concentration of infrastructure and human resources in S&T among the most competitive states, leaving the poorer states with fewer possibilities to integrate with the nanotechnology wave.

Conclusions

Nanotechnology is an emergent technology that has captured the attention of governments in developed and developing countries. Mexico has not been the exception and has taken seriously the use of N&N to improve competitiveness and productivity in scientific-technological material. In analyzing N&N bibliometrics, 12 years after its beginnings in Mexico, we find three relevant tendencies.

First, the great majority of publications are the product of researchers affiliated with public institutions. This could be evidence that businesses do not release to the public that of which they are investigating or that they are not effectively carrying out research on this topic. A more in-depth analysis is required to have a better understanding of this trend. Second, we found that 57 % of the publications were authored by researchers tied to UNAM, UAM, and the CONACYT Centers. This illustrates the dominance of public institutions that have the support of large funding and government endorsement. Third, the inequality in industrial and social development is present in the geographic distribution of N&N publications in Mexico. The states of the center-north of the country have the highest concentration of publications, while the center-south of the nation lags behind significantly in this area.

In the *Science & Technology Special Program 2008–2012* it is specifically noted that science and technology should be put to use for an increase in competitiveness and the reduction of poverty and inequality in Mexico (PECITi 2008). The same document places nanotechnology as one of the tools to achieve that goal. The geospatial distribution of N&N publications shows that nano is following the same tendencies of inequality. This reality, in fact, may lead on to think that technology may contribute to an increase in inequalities, rather than decreasing them.

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