Nanotechnology in Mexico: A conceptual evolution map**

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This article explores the scientific development of nanotechnology in Mexico and is primarily intended to provide information on the state of development and production as evinced by scientific articles and patents. The information is extracted from various databases. Analysis revealed the current state of nanotechnology in Mexico and recent past trends.

Keywords: patents, scientific articles

1. Introduction

Nanotechnology is the manipulation of matter at atomic and molecular scale. The ability to work with matter on such a small scale represents a revolution, since, at this level, matter expresses physical, chemical and biological properties that are quite different from those possessed at a larger scale (Foladori et al., 2012). One of the most promising aspects, as far as the multidisciplinary scientific activity in what we now call nanoscience is concerned, is the ability to control atoms and molecules to form new structures and new materials according to specific needs, or create new alternative sources of energy, and to remedy the ecological damage caused by other technologies, and even to help to alleviate health problems, among many other possibilities. The "nano" prefix refers to scales of size almost a million times smaller than those we can readily observe with the naked eye (10^{-9} m); the *application* of nanoscience is called nanotechnology (Terrones, 2005). The time evolution of nanotechnology is summarized in Figure 1. Nanotechnology should be considered a high-tech, priority sector for national development plans (within the framework of promoting science, technology and innovation) for developing countries, such as Mexico, and not only be considered a discipline for advanced economies.

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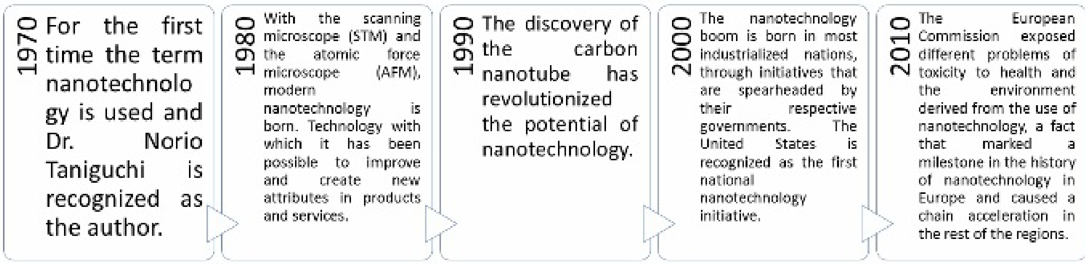

Figure 1. Evolution of the development of nanotechnology (source: ProMexico, 2018).

In the specific case of Mexico, which is the objective of the present study, most of the applications of nanotechnology are concentrated in bionanotechnology, "pure" nanotechnology, nanoengineering, mechanochemistry, nanosynthesis, nanoelectromechanical systems (NEMS), molecular nanotechnology, nanorobotics and nanomedicine, among others (Appelbaum et al., 2016). In spite of some previous analysis on the evolution of nanotechnology in Mexico (Foladori et al., 2012), no conceptual map has been produced in this area, in spite of the importance of having a conceptual system in nanotechnology (Ramsden, 2009), due to the intricate structure of all the areas and subjects covered by the nanosciences. As Appelbaum et al.'s list well illustrates, the plethora of terms used to describe actual work in nanotechnology engenders confusion. Even the question whether "nanoscience" and "nanotechnology" should be singular or plural is under discussion.

2. Policies for nanotechnology in Mexico

From 2001 onwards, research groups active in nanotechnology began to be set up in the Universidad Nacional Autónoma de México (UNAM), the Instituto Potosino de Investigación Científica y Tecnológica (IPICYT), and the Centro de Investigación y Estudios Avanzados del Instituto Politécnico Nacional (CINVESTAV) (Delgado, 2007), among others. However, an important milestone was reached when Mexico joined the Organization for Economic Cooperation and Development (OECD) in 1994. In the same year, various scientific collaboration agreements were signed with the European Union (EU) and individual countries. In Mexico, international scientific collaborations are coordinated by the Consejo Nacional de Ciencia y Tecnología (CONACYT) and this institution has sought to promote research and nanotechnologies in particular. In addition, Mexico has been participating in the International Organization for Standardization (ISO) technical committee on nanotechnology, and in 2007 formed the Comité Técnico Nacional de Normalización en Nanotecnologías (CTNNN) for the regulation of nanotechnologies in the country.

According to different science and technology indicators, Mexico is second in development in nanotechnologies in Latin America, after Brazil and followed by Argentina (Záyago et al.,2013). Nevertheless, expenditure for research and development (R&D) in Mexico is low compared to other OECD member countries. Figure 2 shows the total R&D expenditure (current and capital) as a percentage of total GDP, of all companies, research institutes, and university and government laboratories in the country.

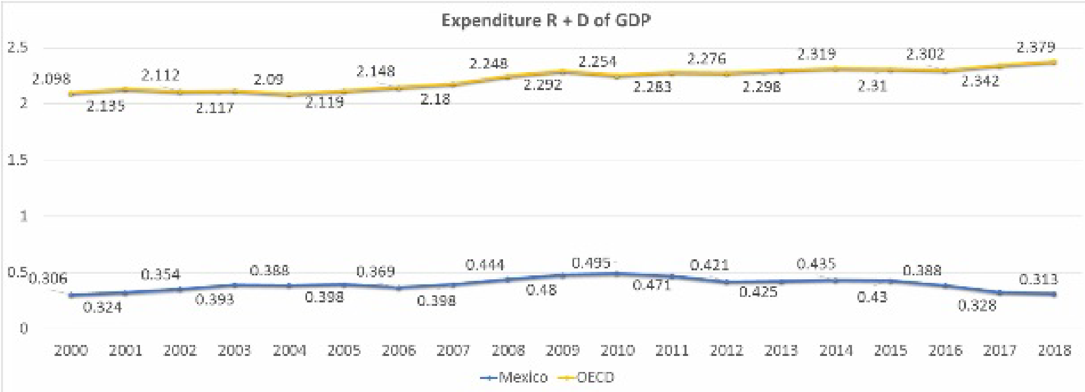

Figure 2. Gross expenditure on R&D (as a percentage of GDP) in Mexico (lower line) compared with the average in OECD member countries (upper line), based on OECD (2020) data.

In 2001, the Government recognized nanotechnologies as a strategic area in its science and technology policies, the *Programa Especial de Ciencia y Tecnología* (PECYT) 2001–2006 (Solleiro, 2002). This plan exposes nanotechnology as a strategic technology with significant development potential, especially in the energy sector through the research and infrastructure capabilities of the *Instituto Mexicano del Petróleo* (IMP) (PECYT, 2001:95).

In 2006 CONACYT convened the scientific and technological community for the presentation of ideas for the realization of megaprojects, with the aim of detecting strategic areas of development for the country. 81 proposals were approved in the first stage, of which five were oriented to nanotechnology (CONACYT, 2006):

- *Laboratorio Nacional de Nanoelectrónica—Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE).*
- *Iniciativa Nacional de Nanotecnología—Universidad Nacional Autónoma de México (UNAM).*
- *Nanotecnología en México como catalizador para impulsar la ciencia y la industria con alto impacto en la sociedad—Instituto Potosino de Investigación Científica y Tecnológica (IPICYT).*
- *Iniciativa Nacional de Nanotecnología (NANOMEX)—Centro de Investigación en Materiales Avanzados (CIMAV).*
- *Plataforma Integral de Investigación y Desarrollo Tecnológico para la Industria Farmacéutica Mexicana (utilizando herramientas biotecnológicas, nanotecnológicas y de ingeniería farmacéutica)—Instituto Tecnológico y de Estudios Superiores de Monterrey (ITESM) Campus Monterrey.*

In 2013, the Consejo Directivo del Centro Nacional de Metrología (CENAM) approved the *Programa de Metrología para las Nanotecnologías* (ProMetNano) with the aim of systematically addressing the country's current and predictable metrological needs, in support of nanosciences and for the use of nanotechnologies (CENAM, 2017).

In October 2014, the Subsecretaría de Competitividad y Normatividad y la Dirección General de Normas (part of the Secretaría de Economía) promulgated the nanotechnology standard NMX-R-80004-1-SCFI-2014: *Vocabulario-Parte 1: Conceptos básicos*, and the standard NMX-R-80004-3-SCFI-2014: *Nanotecnologías—Vocabulario—Parte 3: nano-objetos de carbono* (Foladori et al., 2017).

In Mexico, there are about 80 graduate programmes related to nanotechnology: 36 at PhD level, 43 master's courses, and 12 bachelor's programmes (Foladori et al., 2015; Villavicencio, 2017).

3. The scientific development of nanotechnology in Mexico

Companies that research and/or produce nanotechnology in Mexico have been identified. The companies are concentrated in two geographical areas of the country: Mexico City and the state of Nuevo León (Záyago et al., 2013; Appelabaum et al., 2016). What has made possible the growth of the field of nanotechnology is the creation of research networks involving national and international institutions (Berry, 2003; CIMAV e IPICYT). In addition to the networks there are several national laboratories devoted to nanotechnology, notably the one located in Chihuahua, the Laboratorio Nacional de Nanotecnología (Nanotech), and the one in San Luis Potosí, the Laboratorio Nacional en Nanociencias y Nanotecnología (LI-NAN). In addition, there are clusters or parks specialized in nanotechnology, such as the Paso del Norte Regional MEMS Packaging Cluster, located in the state of Chihuahua and with connexions to the city of Albuquerque in the state of New Mexico (USA); there is also the high-tech industrial conglomerate located in Puebla, which focuses on electromechanical micro–nano systems (MEMS/NEMS) (Robles-Belmont, 2012).

Some of the companies are dedicated to the electricity sector, such as Servicios Condumex located in Mexico City and Viakable in Nuevo León. Regarding domestic appliances, the US company Whirlpool (headquartered in Michigan) has a subsidiary in Mexico with facilities in the Cluster de Nanotecnología de Monterrey (CNNL, 2012). Japan's Sony has a manufacturing line in Tijuana, Baja California; it incorporates nanoscale components into its flat screens and modulators (Cimav, 2008).

Silicon Border Development Science Park (SBDSP) is the first high-tech park specializing in nano components in Latin America. It is in Mexicali, Baja California, and covers 400 hectares. In 2005 the Parque de Investigación e Innovación Tecnológica (PIIT) began to be built in the state of Nuevo León. This park is part of the *Ciudad del Knowledge* project, which is intended to attract Mexico's main educational and research centres to the city of Monterrey. The Universidad Autónoma de Nuevo León (UANL) participates in this project with the Centro de Innovación, Investigación y Desarrollo en Ingeniería y Tecnología's Laboratorio de Nanotecnología y Nanociencias (Záyago & Foladori, 2010). In June 2008 the most advanced nanotechnology cluster in Mexico opened its doors, located near the city of Monterrey with its project *Monterrey Ciudad Internacional del Conocimiento*.

4. Nanotechnology institutions and companies in Mexico

The nanotechnology ecosystem in Mexico (which has a population of almost 130 million) consists of 190 entities in total, including 70 companies, 59 research and development centres both public and private, 53 educational institutions, 7 thematic research networks and 1 specialized cluster that has an incubator of companies in the field (ProMéxico & Secretaría de Economía, 2018). Table 1 lists the academic institutions, research centres and companies that develop nanotechnology, as well as their products, in each state and Figure 3 shows the geographical distribution: it can be clearly seen that Mexico City and Nuevo León have the greatest concentration of institutions that develop nanotechnology in some way.

Table 1. Academic institutions, research centres and companies that develop nanotechnology in Mexico (ProMéxico, 2018).

State	Academic institutions	Research centres	Companies that develop nanotechnology	Products of nanotechnology companies
1	2	3	4	5
Aguascalientes			Frucsomex	Food supplements
			NanoResonance Technology	Water treatment plants
Baja California	FIAD - Facultad de Ingeniería, Arquitectura y Diseño	CICESE - Centro de Investigación Científica y de Tecnologías de la Educación Superior de Ensenada	Bionag	Silver base drug
	TECTIJUANA - Instituto Tecnológico Tijuana	CNyN - Centro de Nanociencias y Nanotecnología	Foxconn Baja California	Nems/Mems
			Vector Vita	Metal
Baja California Sur		CIBNOR - Centro de Investigaciones Biológicas del Noroeste		
Chiapas	UPTAP - Universidad Politécnica de Tapachula			
Chihuahua	UACJ - Universidad Autónoma de Ciudad Juárez	CICTA - Centro de Investigación en Ciencia y Tecnología Aplicada	Interceramic	Coatings
	UTCJ - Universidad Tecnológica de Ciudad Juárez	CIMAV - Centro de Investigación en Materiales Avanzados		
	UTJR - Universidad Tecnológica Junta de los Ríos			
Ciudad de México	ESIQIE - Escuela Superior de Ingeniería Química e Industrias Extractivas	CICATA - Centro de Investigación en Ciencia Aplicada y Tecnología Avanzada	ACS Medio Ambiente	Industrial filters
	IF-UNAM - Instituto de Física de la Universidad Nacional Autónoma de México	CNMN - Centro de Nanociencias y Micro Nanotecnologías	AIG Sinergia y Representaciones	Metal
	IPN - Instituto Politécnico Nacional	ICAT - Instituto de Ciencias Aplicadas y Tecnología	Avon	Cosmetics
	SEPI - Sección de Estudios de Posgrado e Investigación, Unidad Profesional	IFUNAM - Instituto de Física	Beiersdorf	Cosmetics
	SMF DINANO - Sociedad Mexicana de Física, División de Nanociencias	IIM - Instituto de Investigaciones en Materiales	Bridgestone México	Tyres

1	2	3	4	5
	UAM - Universidad Autónoma Metropolitana	INEEL - Instituto Nacional de Electricidad y Energías Limpias	Carl Zeiss AG	Semiconductor
	IBERO - Universidad Iberoamericana	SEPI de ESIME - Sección de Estudios de Posgrado e Investigación de la Escuela Superior de Ingeniería Mecánica y Eléctrica	Comex	Coatings
	UNAM - Universidad Nacional Autónoma de México		Farbitek	Coatings
			Heltec	Industrial filters
			Intel México	Nems/Mems
			Kuo	Polymers
			Mabe	White silver baseline
			Micra nanotecnología	Scanning electron microscopy equipmen
			Motorola México	Nano-enabled end products
			Nanopharmacia Diagnóstica	Cancer diagnostic anesthesis
			Nanotecnología México	Metal
			Neopharma México	Pharmaceutical
			Nestlé México	Industrial filters
			Owens Corning	Coatings
			Plant Health Care de México	Fertilizer
			Powercem México	Cement
			Sadosa	Coatings
			Samsung México	Nanocrystals
			SONY de México	Electronic
			Vamsa	Analytical team
Coahuila	UTC - Universidad Tecnológica de Coahuila	CIQA - Centro de Investigación en Química Aplicada	Nanbios	Nanoencapsulates
Estado de México	ITESM-Estado de México - Instituto Tecnológico y de Estudios Superiores de Monterrey	ININ - Instituto Nacional de Investigaciones Nucleares	Farmaquimia	Chemicals for health, cosmetics and electronics
	UPVM - Universidad Politécnica del Valle de México		Gresmex	Cosmetics
	UTTECAMAC - Universidad Tecnológica de Tecámac		Kaltex	Textile fiber
	Universidad Tecnológica de Zinacantepec		Máxima -Adhesivos	Coatings
	UTFV - Universidad Tecnológica Fidel Velázquez		Nanometrix	Analytical and scientific equipment and instruments
			Nanonutrition	Nutraceutical
			NANOX Bardahl	Oils and additives

1	2	3	4	5
Guanajuato	GTP - Guanajuato Tecno Parque	CIATEC - Centro de Innovación Aplicada en Tecnologías Competitivas	Lotto Bio Nano Laboratories	Metal
	UG - Universidad de Guanajuato	CIO - Centro de Investigaciones en Óptica	Wurth Elektronic	Electrical components
Hidalgo	UAEH - Escuela Superior de Apan		Nanocron	Metal
	UAEH - Universidad Autónoma del Estado de Hidalgo		Ten-Pac	Textiles
	UTTT - Universidad Tecnológica de Tula - Tepeji			
	UTEC - Universidad Tecnológica de Tulancingo			
	UTTT - Universidad Tecnológica Tula-Tepeji			
Jalisco	CUVALLES - Centro Universitario de los Valles	CIATEJ - Centro de Investigación y Asistencia en Tecnología y Diseño del Estado de Jalisco, Sede Guadalajara	Carbotecnia	Industrial filters
	CUTONALA - Centro Universitario de Tonalá	CIATEJ - Centro de Investigación y Asistencia en Tecnología y Diseño del Estado de Jalisco, Sede Zapopan	Kurago Biotek	Chemicals for health and nutrition
Michoacán	ITCH - Instituto Tecnológico Superior Ciudad Hidalgo	IFM - Instituto de Física y Matemáticas		
	UCEMICH - Universidad de La Ciénega del Estado de Michoacán de Ocampo	IIM - Instituto de Investigaciones en Materiales		
	UMSNH - Universidad Michoacana de San Nicolás de Hidalgo	IIQB - Instituto de Investigaciones Químico-Biológicas		
Morelos	UAEM - Facultad de Ciencias de la Universidad Autónoma del Estado de Morelos	CInC - Centro de Investigación en Ciencias	Laboratorios de Especialidades Genómicas	Genetic chemistry
	UNAM - Morelos - Universidad Nacional Autónoma de México, Campus Morelos	CIICAp - Centro de Investigación en Ingeniería y Ciencias Aplicadas	Permanere et Renovare Salutis	Pharmacists and veterinary products
	UTEZ - Universidad Tecnológica Emiliano Zapata del Estado de Morelos	INEEL - Instituto Nacional de Electricidad y Energías Limpias		
Nayarit		CICESE - Centro de Investigación Científica y de Educación Superior de Ensenada, Unidad Nayarit		
		CICESE-UT3 - Unidad de Transferencia Tecnológica, Tepic		

1	2	3	4	5
Nuevo León	ITESM-Monterrey - Instituto Tecnológico y de Estudios Superiores de Monterrey	CB FEMSA - Centro de Biotecnología Femsa	Aqua-Pro	Industrial filters
	PIIT - Parque de Investigación e Innovación Tecnológica	CIDESI - Centro de Ingeniería y Desarrollo Industrial	Cemex Central	Cement
	UANL - Universidad Autónoma de Nuevo León	CIIDIT - Centro de Innovación, Investigación y Desarrollo en Ingeniería y Tecnología	Centro de Desarrollo de Tecnología de Sigma Alimentos	Food packaging
	UTE - Universidad Tecnológica Gral. Mariano Escobedo	CIMAV - Centro de Investigación en Materiales Avanzados	Global Proventus	Industrial filters
		CIATEJ - Centro de Investigación y Asistencia en Tecnología y Diseño del Estado de Jalisco, Sede Apodaca	Industrias Vago De México	Seals for mechanical parts
		CETIV - Centro de Tecnología e Investigación Viakable	Kemcare de México	Oils and emulsions
		CEPCE - Centro para la Productividad y Competitividad Empresarial	La Cantera Proyectos y Arquitectura	Coatings
		CIBYN - Centro de Investigación en Biotecnología y Nanotecnología	Lubricantes de América	Seals for mechanical parts
		i2t2 - Instituto de Innovación y Transferencia Tecnológica de Nuevo León	Nanomateriales	Coal, polymers, non-metallic minerals, metals and dendrers
		INEEL - Instituto Nacional de Electricidad y Energías Limpias	Nemak	Metalworking
			Sanitarios Lamosa	Coatings
			Scanpaint	Food packaging
			Sigma Alimentos	Coatings
			Viakable	Electric conductors
			Vitro	Coatings
			Whirpool México	White silver baseline
Puebla	NANO-BUAP - Centro de Nanotecnología de la BUAP	INAOE - Instituto Nacional de Astrofísica, Óptica y Electrónica		
	UDLAP - Fundación Universidad de las Américas Puebla			
	ITESM-Puebla - Instituto Tecnológico de Estudios Superiores de Monterrey			
	UDLAP - Universidad de las Américas Puebla			

1	2	3	4	5
Querétaro	UAQ - Universidad Autónoma de Querétaro	CFATA - Centro de Física Aplicada y Tecnología Avanzada	Provista	Polymers
	UTEQ - Universidad Tecnológica de Querétaro	CIDESI - Centro de Ingeniería y Desarrollo Industrial		
		CICATA - Centro de Investigación en Ciencia Aplicada y		
		CIATEQ - Centro de Investigación y Asistencia Técnica		
		CINVESTAV - Centro de Investigación y de Estudios Avanzados		
		CIDETEQ - Centro de Investigación y Desarrollo Tecnológico en Electroquímica		
		CENAM - Centro Nacional de Metrología		
San Luis Potosí	ITESM-SLP - Instituto Tecnológico de Estudios Superiores de Monterrey	CICSaB - Centro de Investigación en Ciencias de la Salud y Biomedicina	Datiotec	Nanosatellites
	UASLP - Universidad Autónoma de San Luis Potosí	CIATEQ - Centro de Investigación y Asistencia Técnica	Viretec gestión y desarrollo	Nanotechnology services
	UPSLP - Universidad Politécnica de San Luis Potosí	CIACYT - Coordinación para la Innovación y la Aplicación de la Ciencia y la Tecnología		
		IPICyT - Instituto Potosino de Investigación Científica y Tecnológica		
Sinaloa	UPSIN - Universidad Politécnica de Sinaloa			
Sonora	UNISON - Universidad de Sonora	CIAD - Centro de Investigación en Alimentación y Desarrollo	RD Research & Technology	Nems/Mems
			Rubio Pharma y Asociados	Nutraceutical
Tabasco	UJAT - División Académica Multidisciplinaria de Jalpa de Méndez	CIATEQ - Centro de Investigación y Asistencia Técnica		
Tamaulipas	Universidad Tecnológica de Altamira	CICATA - Centro de Investigación en Ciencia Aplicada y Tecnología Avanzada, Unidad Altamira	Mesil	Disinfectants
		CINVESTAV - Centro de Investigación y de Estudios Avanzados		
Tlaxcala		CIBA - Centro de Investigación en Biotecnología Aplicada		

1	2	3	4	5
Veracruz	ITSPOZARICA - Instituto Tecnológico Superior de Poza Rica	MICRONA - Centro de Investigación en Micro y Nanotecnología		
	UTCV - Universidad Tecnológica del Centro de Veracruz	INEEL - Instituto Nacional de Electricidad y Energías Limpias		
Yucatán	UAY - Universidad Autónoma de Yucatán	CICY - Centro de Investigación Científica de Yucatán	Oficina Mexicana de Transferencia de Tecnología Innovación y Conocimiento	Innovation in biotechnology, health and IoT
		CIATEJ - Centro de Investigación y Asistencia en Tecnología y Diseño del Estado de Jalisco, Sede Mérida		
		CINVESTAV - Centro de Investigación y de Estudios Avanzados		

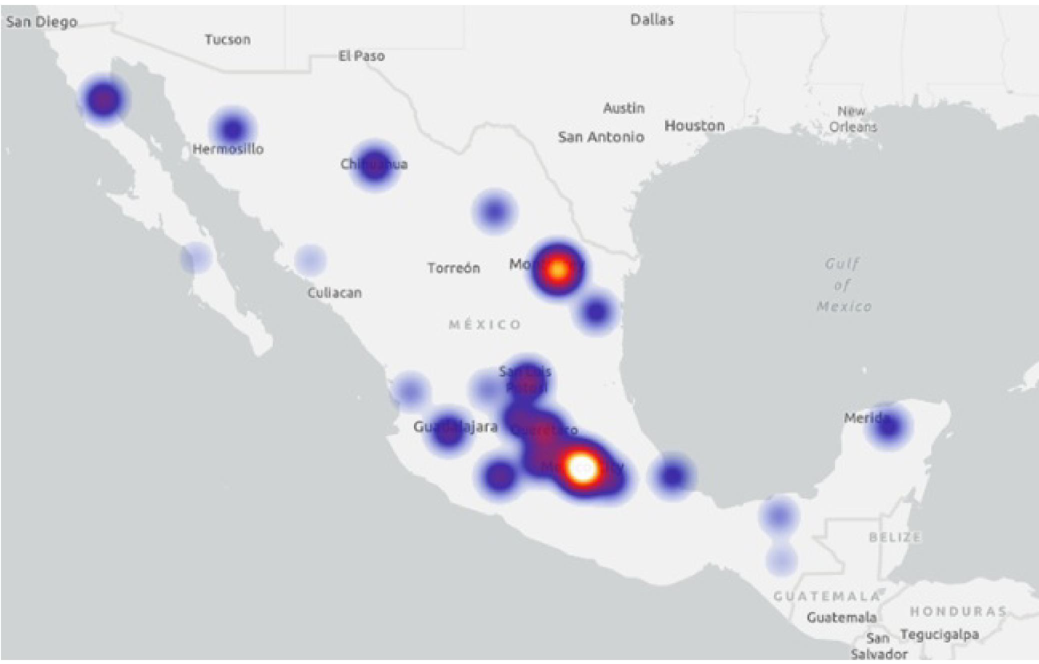

Figure 3. Academic institutions, research centers and companies that develop nanotechnology in Mexico. Light blue indicates few activities and, successively, dark blue, red and white indicate increasing activity. Source: own elaboration with ProMexico data, 2018.

Although networks and clusters do not themselves comprise any physical infrastructure, beyond a usually modest secretariat ("HQ", which is often hosted within another organization), those devoted to nanotechnology are worth mentioning (ProMéxico, 2018):

- **BIONN—Red Internacional de Bionanotecnología:** with HQ located in Baja

California and created in 2012 it is one of CONACYT'S thematic networks with more than 200 participants in 35 thematic groups (90 national and international institutions in nanotechnology);

- **RCNMN—Red del Centro de Nanociencias y Micro y Nanotecnologías del IPN:** HQ located in Mexico City with about 100 members working on projects oriented to innovation and the development of nanotechnology;
- **DINANO—División de Nanociencias y Nanotecnología de la SMF:** HQ located in Mexico City—created to foster collaboration and exchange of experience between researchers and nanotechnology students;
- **Red de Nanociencias de la UAM:** HQ located in Mexico City and created a decade ago with around 50 researchers—the network aims to obtain and disseminate information about nanoscience and nanotechnology;
- **Red Convergencia—Red de Convergencia Tecnológica:** HQ located in Mexico City—although this organization does not devote its full focus to nanotechnology, its intervention in the field has been a great support in adumbrating a technological scenario in which various general-purpose technologies converge to create innovative technological solutions;
- **RNyN—Red de Nanociencias y Nanotecnología:** with HQ located in Querétaro and led by UNAM in collaboration with CONACYT, it is the largest of its kind nationally, involving more than 500 researchers from more than 15 academic institutions and national and international research centres—through the work of interdisciplinary teams it aims to research, develop and generate high-impact knowledge in nanotechnology;
- **ReLANS—Red Latinoaméricana de Nanotecnología y Sociedad***:* HQ located in Zacatecas and consists of more than 50 scientists from different countries of the Americas, with liaison and coordination carried out by the Autonomous University of Zacatecas. The work of this network has served to achieve better understanding of the role of nanotechnologies in national development, as well as foster progress and enhance impacts at the regional level, through discussion forums and information exchanges;
- **CNNL—Clúster de Nanotecnología de Nuevo León:** the cluster was initiated in 2008 under the "triple helix" model, involving institutions in the industrial, academic and governmental sectors. Its objective is to contribute to sustainable economic development through the application of nanotechnology, by strengthening production chains linked to materials, by the creation and reinforcement of new companies, and by the training of human capital to help bring to market projects based on nanotechnology.

Some of the companies contributing to the development of nanotechnology standards and protocols in Mexico are (Red Nacional de Nanociencia y Nanotecnología, 2018): Farmaquimia, FEI, Gresmex, Lotto Bio Nano Laboratories, Micra Nanotecnología, Nanomateriales, VIRETEC, NanoCoatings Technologies and Zeiss.

5. Scientific articles and patents on nanotechnology in Mexico

Numbers of patents and published scientific articles are one of the most widely used indicators for measuring innovation and competitiveness in technical fields. Through scientific databases one can explore the output of nanotechnology-related information in Mexico over the past 10 years. Results are given in Table 2.

Table 2. Mexican articles on nanotechnology in different databases. Search criteria were: TITLE-ABS-KEY (nanotechnology) AND PUBYEAR > 2009 AND (LIMIT-TO ("Mexico" & "MX")).

Database	Total found
Web of Science	410 articles
Scopus	835 articles
ScienceDirect	2,804 articles
Google Scholar	999 articles
Google Patents	1,951 patents

Numbers of articles are only the first step, however. Comprehensive literature reviews are one of the most important elements of any more advanced analysis. The objective of such a review is to map out and evaluate the relevant literature in order to identify possible research trends that are useful for strengthening the conceptual framework (Tranfield et al., 2003; Aguado-Cortes and Castaño, 2020). Bibliometric analysis is a research technique already validated in fields such as informatics and other new technologies (Wagner et al., 2011; Paiva Dias 2014); trends in knowledge are identified with quantitative techniques that efficiently analyse digital databases. For administrators and decision-makers in an organization, such analysis is an important guide to formulating policy and strategy by noting trends in global operations.

Figure 4 shows the numbers of articles relating to nanotechnology published by scientists in Mexico in the last 10 years in the most-favoured journals. Figure 5 shows the year-by-year growth over the past 10 years of scientific articles on nanotechnology; the average annual growth rate is 8.8%. Figure 6 shows the most frequently occurring keywords of the articles found in the databases; perhaps unsurprisingly "nanoparticles" and "properties" are the leading keywords. Figure 7 provides a temporal dimension for some of the journals listed in Figure 4, with the *Journal of Hydrogen Energy* the preferred medium in 2018 with 54 articles. It is interesting to notice that hydrogen research is so dominant, but spending seems to be falling rather fast due to changes in the Mexican Federal Administration's policies for alternative energies. Figure 8 shows the most prolific authors in topics related to nanotechnology and the numbers of their articles published. In Figure 9, we can see how selected pertinent keywords have developed over time. In Figure 10 we can see the trends of nanotechnology over the last 10 years as evidenced by the frequency of occurrence of the most common keywords.

Figure 11 shows which institutions publish the most in nanotechnology topics. In the top place we have the *Universidad Nacional Autónoma de México* with 140 articles, followed by *Instituto Politécnico Nacional* (48), *Universidad Autónoma Metropolitana* (47), *Universidad Autónoma de Zacatecas* (43), *Universidad de Guadalajara* (40), *Tecnológico de Monterrey* (38), *Universidad Autónoma del Estado de México* (36), *Universidad de Sonora* (35), *Universidad Autónoma del Estado de Morelos* (32), *Universidad Autónoma de Nuevo León* (27), *Universidad Autónoma de San Luis Potosí* (23) and the *Centro de Investigación y de*

Estudios Avanzados (CINVESTAV) with 21 articles. The main areas of research in nanotechnology also emerge from this analysis (Figure 12): materials science with 140 articles, science technology—other topics with 110, chemistry with 109, physics with 80, engineering with 70, pharmacology & pharmacy with 41, biochemistry & molecular biology with 37, food science & technology with 34, polymer science with 19 and agriculture with 17 articles. Figure 13 shows the countries with which Mexico has collaborated in the domain of nanotechnology, with collaboration intensity evidenced by the number of articles cosigned by researchers from the foreign country: USA (223 articles), Spain (74), France (31), Brazil, India and China (each 27), Italy (24), Russia (22), Canada (20) and Argentina with 18 articles.

Figure 14 shows the evolution of published patents that have been found on Google Patents over the past 10 years, and Figure 15 shows the clouds of words generated from the content and keywords of the patents found over that interval.

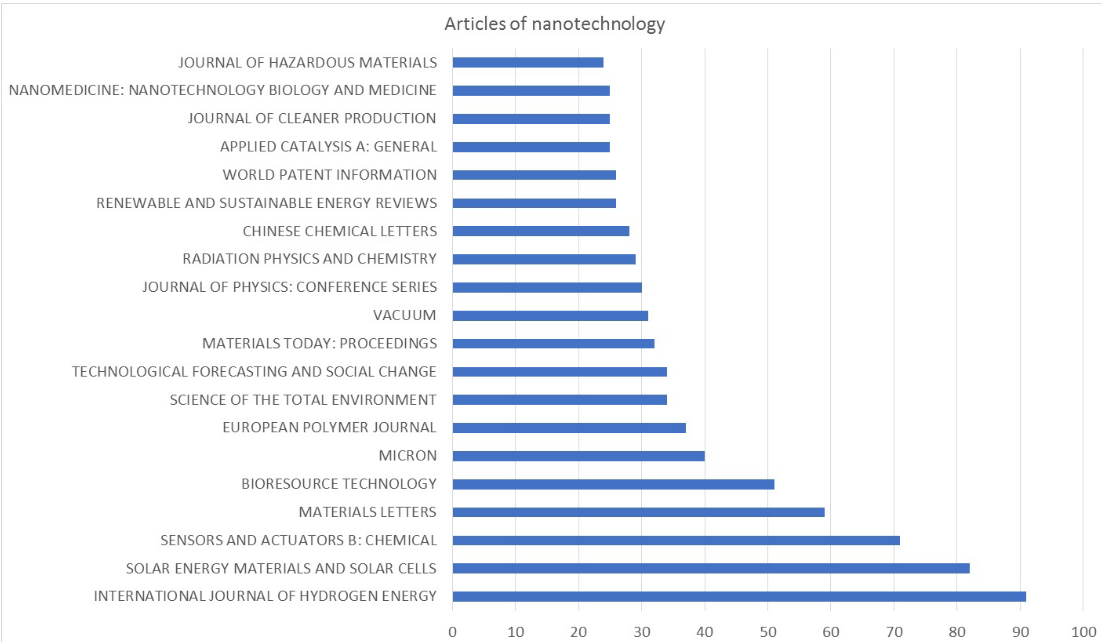

Figure 4. Published articles relating to nanotechnology from Mexican institutions 2010–20 (up to data available in December 2020). The horizontal scale gives the number of articles in the listed journal.

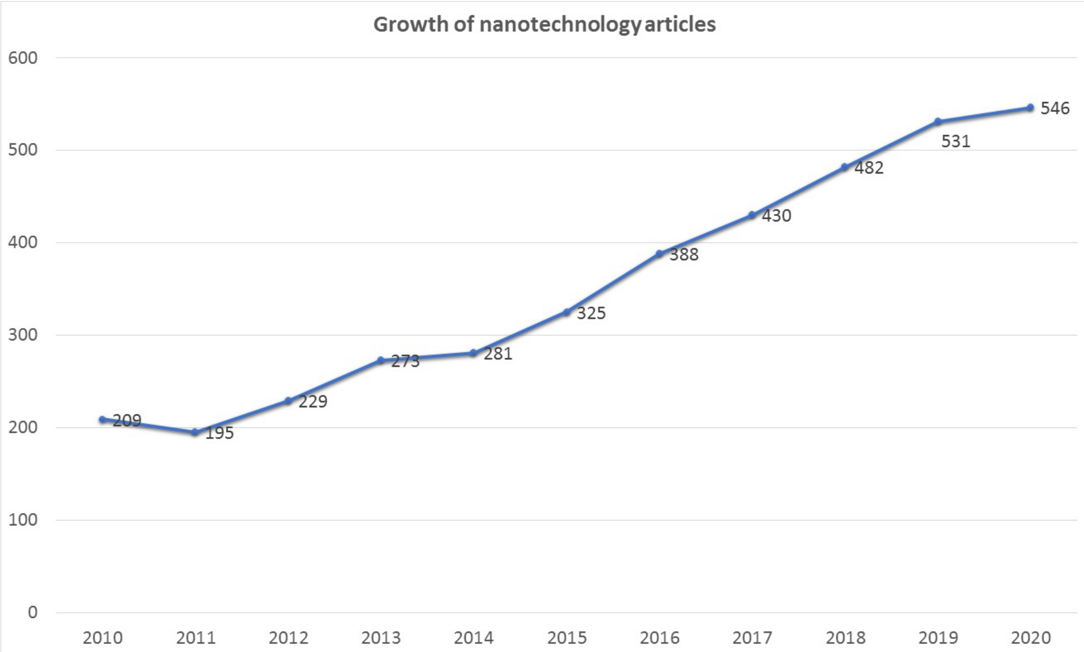

Figure 5. Total numbers of Mexican nanotechnology articles published 2010–20.

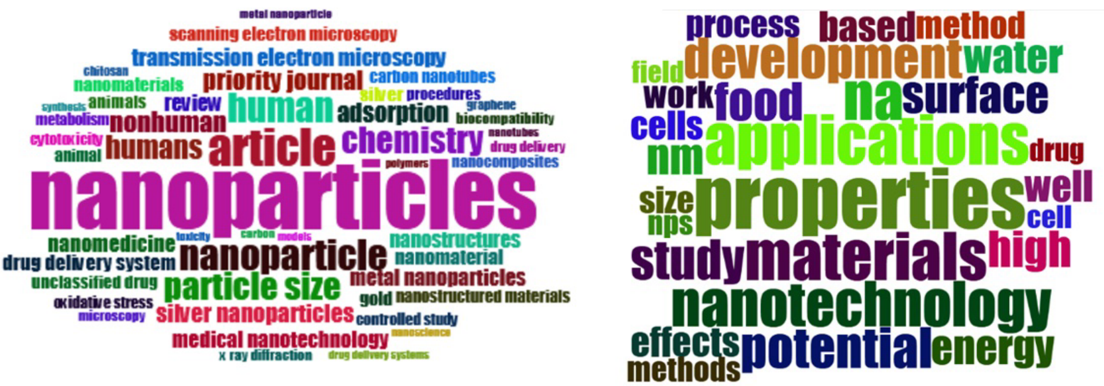

Figure 6. Nanotechnology keywords for Mexican articles 2010–20, according to the databases Web of Science, Scopus, ScienceDirect and Google Scholar. The size of each word is proportional to its number of occurrences. Left, methodologies and characterization; right, fields of application.

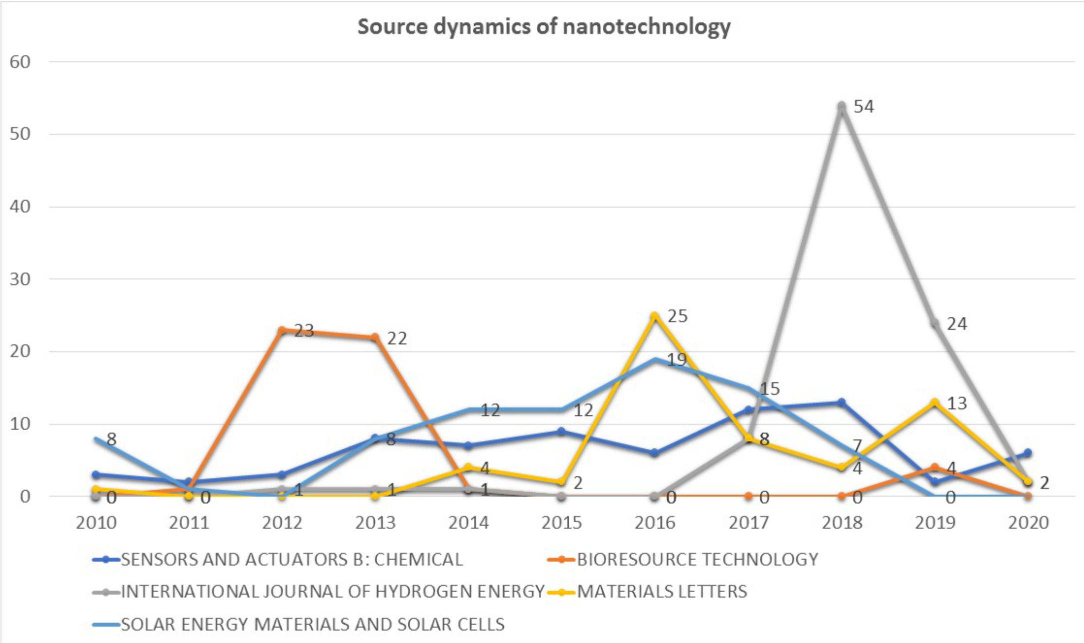

Figure 7. Source dynamics of Mexican nanotechnology articles appearing in selected journals in the interval 2010–20.

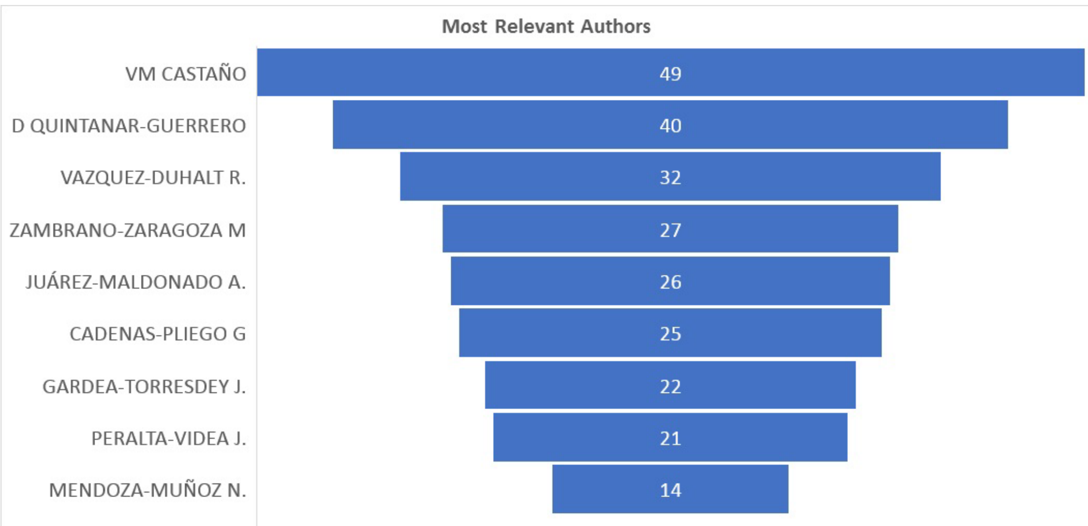

Figure 8. Most prolific authors in Mexico publishing on nanotechnology, 2010–20.

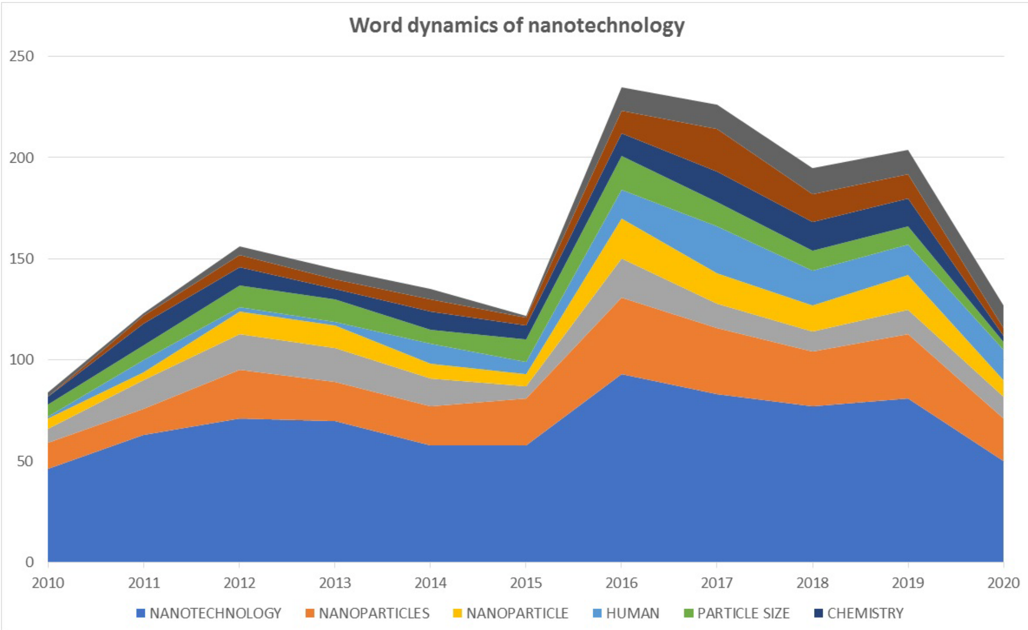

Figure 9. Dynamics of the most frequently occurring keywords for Mexican nanotechnology articles, 2010–20.

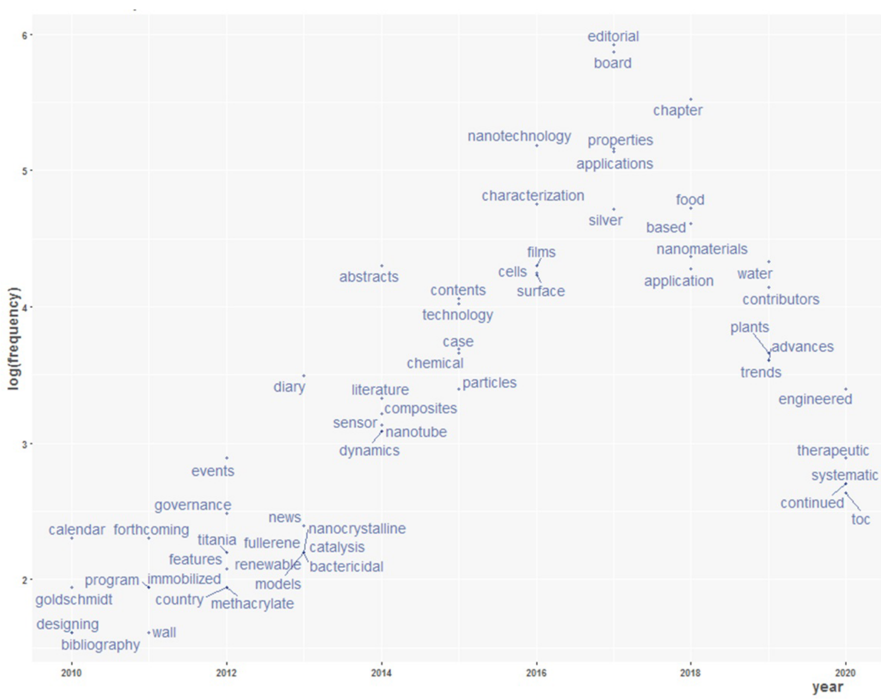

Figure 10. Trend topics of nanotechnology in Mexican articles, 2010–20.

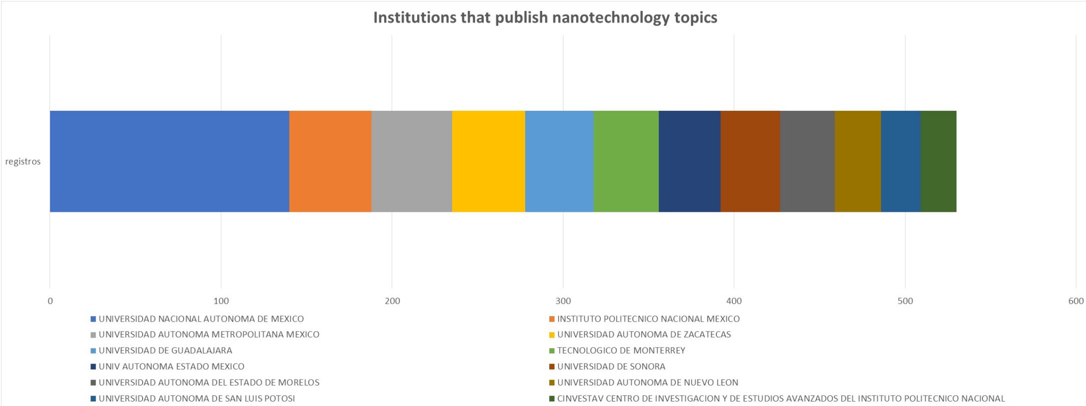

Figure 11. Mexican institutions publishing work on nanotechnology topics (see main text) , 2010–20.

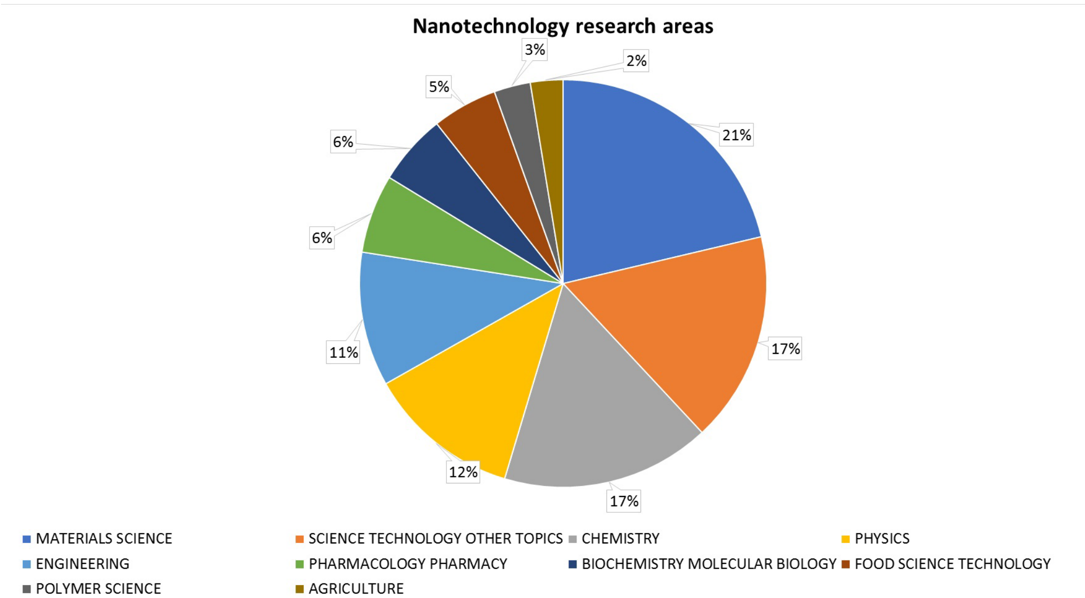

Figure 12. Nanotechnology research areas covered by Mexican articles, 2010–20.

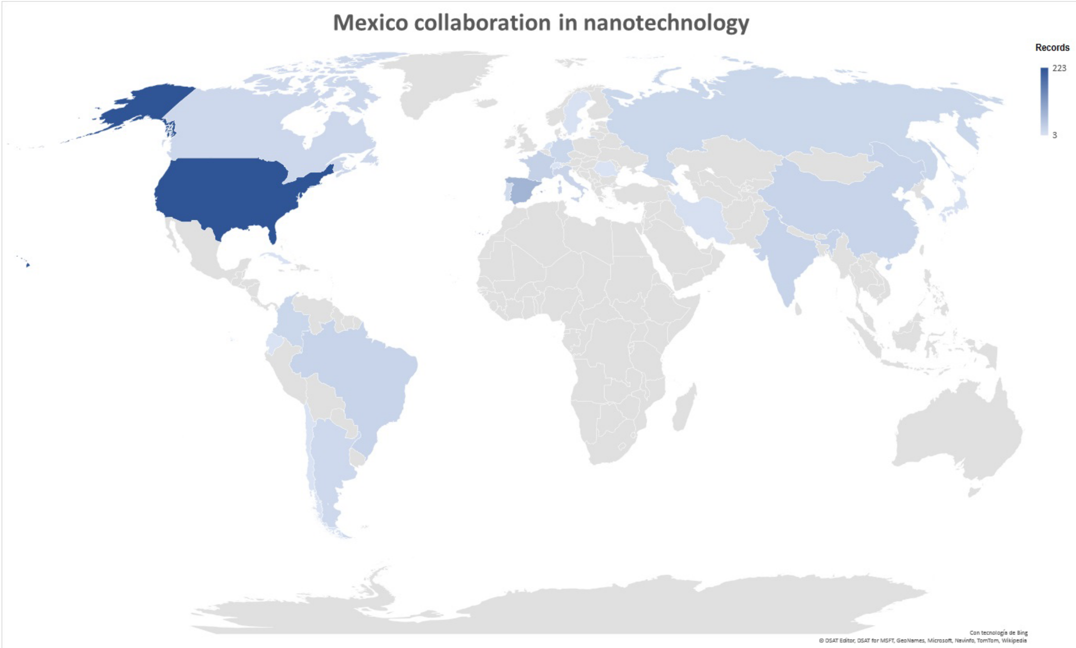

Figure 13. Mexico's international collaboration in nanotechnology, 2010–20. The saturation (chroma) of the colour represents the intensity, as evinced by the numbers of joint articles (see main text).

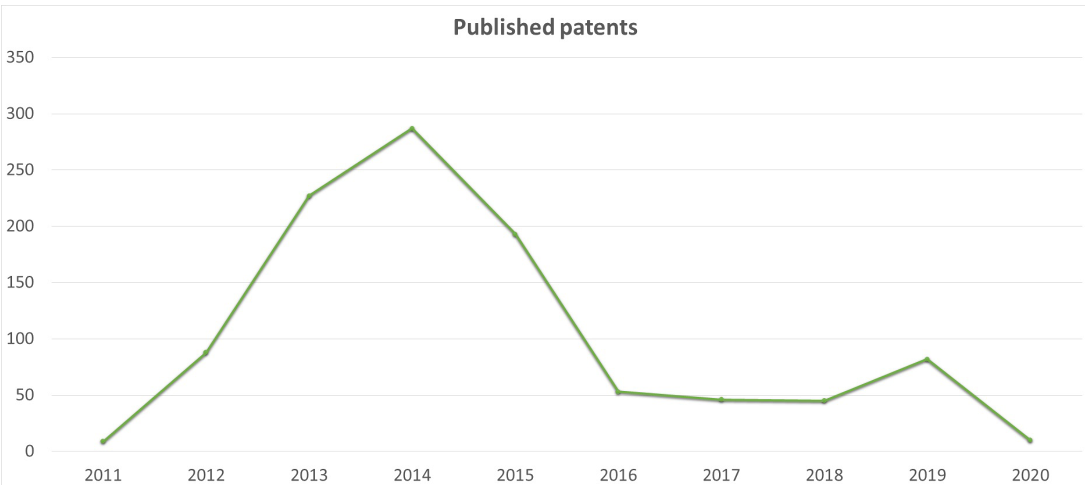

Figure 14. Mexican published patents 2010–20 (as found from Google Patents).

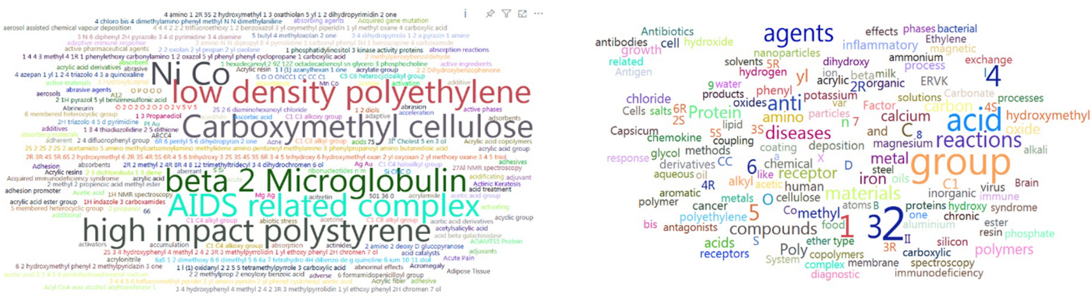

Figure 15. Word clouds representing Mexican patents, 2010–20. Left, materials science and engineering applications; right, biomedical applications.

6. Concluding remarks

Mexico has dedicated significant resources to support nanoscience, which is resulting in growing activity in nanotechnology, both academical and industrial. Clusters, networks and industrial parks have encouraged useful synergies.

We infer that nanotechnology is embedded in Mexico's industrial development in key economic areas. In particular, nanotechnology promises to be a fundamental part of Industrie 4.0, which already has two important hubs in Nuevo León and in the Centro-Occidente region (Querétaro, Guanajuato, Jalisco, Zacatecas and Aguascalientes). We believe our findings to be relevant not only from an academic standpoint, but also as a tool for geopolitical public policy decisions.

These conclusions are far from exhaustive. Clearly more detailed correlations could be established and interpreted with the help of specific local knowledge. We hope that the data presented will encourage readers to develop further conclusions. Our primary aim, however, was to use readily accessible scientometric data to present an extended snapshot of nanotechnology in a country at the developing/developed boundary that might be especially well placed to exploit and benefit from nanotechnology.

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