Journal of the Professional Association for Cactus Development

Agronanotechnology in the arid zones of northern Mexico: Research, challenges, and new trends

Mónica Anzaldo Montoya[1], Yoscelina Iraida Hernández-García[2], Luis Guillermo Hernández-Montiel[3], Luis Hernández-Adame*[3,4]

[1] CONAHCYT-El Colegio de San Luis A.C., San Luis Potosí, México, Parque de Macul #155, Fracc. Colinas del Parque, San Luis Potosí, S.L.P., México. C.P. 78294, México.
[2] Centro de Investigación y de Estudios Avanzados, Programa de Doctorado Transdisciplinario en Desarrollo Científico y Tecnológico para la Sociedad, Av. Instituto Politécnico Nacional 2508, San Pedro Zacatenco, Gustavo A. Madero, 07360 Ciudad de México, México.
[3] Grupo de Nanotecnología y Biocontrol Microbiano, Centro de Investigaciones Biológicas del Noroeste, La Paz 23096, Baja California Sur, México.
[4] CONAHCYT-Centro de Investigaciones Biológicas del Noroeste, Instituto Politécnico Nacional 195, Playa Palo de Santa Rita Sur, La Paz, B.C.S., 23096, México.
*Corresponding author: ladame@cibnor.mx (L. Hernández-Adame)

Citation: Anzaldo-Montoya, M., Hernández-García, Y.I., Hernández-Montiel, L.G. and Hernández-Adame, L. 2024. Agronanotechnology in the arid zones of northern Mexico: Research, challenges, and new trends. *Journal of the Professional Association for Cactus Development. 26*: 1-29. https://doi.org/10.56890/jpacd.v26i.534

Associate Editor: Pablo Preciado-Rangel

Technical Editor: Tomas Rivas-Garcia

Received date: 28 August 2023

Accepted date: 02 December 2023

Published date: 19 January 2024

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Abstract. The agri-food systems in arid zones face challenges related to climate change, desertification, and soil contamination from agrochemicals' actions, among others. The agronanotechnology can generate alternatives to these problems, but it is necessary to monitor its development to have elements to apply policies that are oriented to the attention of these regions with a social perspective. This scientific paper aims to present provide a study of the situation of agronanotechnology in the arid zones of northern Mexico. Using bibliometric tools, the academic output in the field and map the public research agenda, focusing on providing the set of crops to which the local research is directed was analyzed. Furthermore, the literature associated with the risks to human health and the environment derived from some nanomaterials of agri-food interest and clarify the areas of opportunity and trends was reviewed. The results show a total of 224 research articles authored by 1029 scholars in 161 journals published from 2004 to 2022; that research on this topic reached its highest value in 2018 and then levels off at a value around of ~37%. The findings show a research agenda related to crops of economic interest for the export market like tequila, tomato, avocado, chili, watermelon. In México, agronanotechnology is an emerging field that deals with some crops of economic interest, but its development needs to be intertwined with the needs of rural producers*.*

Keywords: *agronanotechnology, arid zones, food safety, nanomaterials, nanoscience.*

Introduction

The arid zones are geographic extensions in which the low availability of water in the soil and humidity in the environment are their main characteristics. Usually, these zones have high water evaporation rates with high levels of solar radiation, which favor the formation of highly alkaline soils due to the accumulation of carbonates with electrical conductivity levels that reach up to 8 dS m^{-1} (Martínez-Ruiz *et al.,* 2016). In Mexico, 52% of the territory corresponds to arid or semi-arid zones, located mainly in the northern states, Baja California, Baja California Sur, Chihuahua, Sinaloa, Sonora, Durango, San Luis Potosí, Coahuila, Nuevo León, Tamaulipas, and Zacatecas. The arid zones of the country have low precipitation, between 50 and 230 mm of rain per year, accompanied by extreme temperatures that range between 38 and 52 °C in the summer months (Márquez-Berber *et al.,* 2006).

Under these characteristics, agricultural production in arid zones constantly challenges small and large-scale farmers, including subsistence agriculture. Despite adverse conditions, the arid zones of northern Mexico contribute 39% of the country's agricultural production value (SIACON, 2021). The table 1 shows a summary of the main agricultural products harvested in this region, including edible cacti and their derived fruits which, although little studied, possess important nutritional properties and can represent a significant economic contribution to the region's agrifood sector (Corso-Rios *et al.,* 2016). Other agricultural activities in this region are of economic and cultural importance, such as cattle and goat raising, aquaculture, and dairy production.

The biophysical characteristics and socioecological conditions of the arid zones constantly challenge agricultural production. Currently, the region faces effects related to climate change, desertification, and soil contamination by agrochemicals, among others. The research in agronanotechnology can generate alternatives to these problems; however, monitoring its development from an interdisciplinary perspective is necessary to establish governance that links research agendas with the demands of the regional productive and social sectors (Bhandari *et al.,* 2023). The bibliometrics is a reliable approach for assessing scientific production and research agendas through systematically identifying, selecting, and analyzing references. The bibliometrics uses statistics to describe publishing trends and to highlight relationships between published works (Ninkov *et al.,* 2022). It is widely used to map the dynamic of science and compare countries and institutions (Gingras, 2021). The bibliometric methods and tools are particularly important to all science and technology fields due to the increasing speed at which knowledge and scientific publications are produced currently (Aria and Cuccurullo, 2017); at the same time, this information needs to be related with decision making.

Recently, some studies in agronanotechnology used bibliometrics (Stopar, 2016; Hugar, 2020; Liu *et. al*., 2023; Lakner *et al*., 2021). However, there are still very few studies related to arid areas. It was possible to identify only two reports. One performs a bibliometric analysis about stress factors affecting agricultural productivity globally (Sisodia *et al.,* 2023) and the other one is a bibliometric analysis describing the progress of piosphere knowledge and its implications for conservation and scientific collaboration (Shahriary *et al.,* 2021). Bibliometric studies carried out in México on agronanotechnology neither on arid zones did not find. The agriculture and food production face enormous challenges, so a local perspective of the development of agronanotechnology can be helpful to scholars and different stakeholder in order to take informed decisions.

The aim of this scientific paper is to present a study of the situation of agronanotechnology in the arid zones of northern Mexico. The study includes an overview of the characteristics of agronanotechnology as a line of research, and its main applications; an analysis of the academic output in the field and a map of the public research agenda. Furthermore, we review the literature associated with the risks to human health and the environment derived from some nanomaterials, included the status of nano-standardization.

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This scientific paper is organized as follows, section 2 describes the methods; section 3 describes the results and discussion; section 4 describes the challenges and trends for nanotechnology in the agricultural sector, and section 5 presents the conclusions.

Material and Methods

The bibliometric analysis was performed using the Web of Science (WoS) database. Furthermore, the corresponding literature on agronanotechnology and its relationship with social, environmental, and regulatory aspects in Mexico was reviewed.

The bibliometric analysis was performed on the Web of Science platform using the search strategy described in Table 2. This search was applied to WoS topic search (TS), including the paper title, abstract, and keywords. The search query was conducted in July, 2023. A total of 615 documents were obtained (including articles, books, book chapters, reviews, and conference papers) from 2004 to 2022. The records obtained went through a manual review process of eliminating duplicates and papers unrelated to the topic of study, finally getting a total of 425 documents.

In a separate process, the names of the states in Mexico that appear in the affiliation field were identified and standardized to identify the scientific production of those that correspond to the arid zones of Northern Mexico mentioned previously, obtaining a total of N=224 papers published by academic institutions in the region under study (Baja California, Baja California Sur, Chihuahua, Sinaloa, Sonora, Durango, San Luis Potosí, Coahuila, Nuevo León, Tamaulipas, and Zacatecas). Analyses were conducted using Biblioshiny, a web interface for bibliometrix (Aria and Cuccurullo, 2017). Graphs were produced using either Microsoft Excel or Datawrapper.

Results and Discussion

The bibliometric analysis

The table 3 shows the main indicators of the bibliometric data. The published works comprised 224 documents, 1029 authors from 2004 to 2022, with an average yearly publication of 5.15, average citations per document of 30.63, and an international co-authorships percentage of 36.44. The most productive and cited authors are identified in table 3, respectively.

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Table 1. Main agricultural products harvested in the arid zones of northern Mexico.

Agricultural products	Baja California	Baja California Sur	Coahuila	Chihuahua	Durango	Nuevo León	San Luis Potosí	Sinaloa	Sonora	Tamaulipas	Zacatecas
Shriveled alfalfa *Medicago sativa*	✓	✓		✓							
Green Alfalfa *Medicago sativa*			✓		✓		✓				
Cotton *Gossipyum*			✓	✓							
Oat as Green Fodder *Avena sativa*					✓						
Barrel cactus *Echinocactus grusonii*										✓	
Sugar cane *Saccharum officinarum*							✓			✓	
Onion *Allium cepa*	✓										
Dried chili *Capsicum*							✓				✓
Green chili *Capsicum*		✓						✓			
Jiotilla *Escontria chiotilla*									✓		
Asparagus *Asparagus officinalis*		✓							✓		
Strawberry *Fragaria*	✓										
Bean *Phaseolus vulgaris*					✓			✓			✓
Maize green forage *Zea mays*			✓		✓						✓
Maize *Zea mays*				✓	✓			✓	✓	✓	✓
Apple *Malus domestica*				✓							
Orange *Citrus sinensis*						✓				✓	
Nopalitos	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

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Agricultural products	Baja California	Baja California Sur	Coahuila	Chihuahua	Durango	Nuevo León	San Luis Potosí	Sinaloa	Sonora	Tamaulipas	Zacatecas
Opuntia ficus-indica											
Nut *Juglans*			✓	✓		✓					
Potato *Solanum tuberosum*		✓				✓		✓	✓		
Pastures and Meadows *Cydonon dactylon*						✓	✓			✓	
Saguaro *Carnegiea gigantea*									✓		
Grain sorghum *Sorghum*										✓	
Grain wheat *Triticum*	✓								✓		
Tuna Alfajayucan *Opuntia albicarpa*							✓				✓
Tuna amarilla Opuntia ficus indica		✓					✓				✓
Tuna blanca burrón Opuntia oligacantha							✓				✓
Tuna blanca crystalline *opuntia albicarpa*							✓				✓
Tuna criolla *Opuntia ficus indica*					✓						
Tuna roja *Opuntia megacantha*							✓				✓
Grapes *Vitis Vinifera*									✓		

Source: Data from Consultation Agrifood Information System (SIACON) up to June 2023. The symbol indicates crop´s production in the state.

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Table 2. Bibliographic recovery at web of science.

Search strategy	Filters
ts=(nano* AND (fertiliz* OR agriculture OR agro()chemicals OR pesticides OR novel()food processing or feed()processing OR food delivery()systems OR nanocides OR agrochem* NOT drug delivery NOT biomedic* NOT drug release)) AND cu=mexico	Exclude – Web of Science Categories: Clinical Neurology or Endocrinology Metabolism or Entomology or Fisheries or Medicine General Internal or Medicine Research Experimental or Oncology or Parasitology or Reproductive Biology or Veterinary Sciences or Virology or Allergy or Agriculture Dairy Animal Science or Neurosciences or Marine Freshwater Biology or Infectious Diseases or Immunology or Pharmacology Pharmacy or Nutrition Dietetics or Public Environmental Occupational Health. and Exclude – Research Areas: Genetics Heredity or Life Sciences Biomedicine Other Topics or Pharmacology Pharmacy.

Table 3. Main Indicators of the articles collected.

Indicator	Results
Timespan	2004:2002
Sources (Journals, Books, etc)	161
Documents	224
Average years from publication	5.15
Most frequent Trend Topics	Nanoparticles; nanotechnology; antioxidants; silver nanoparticles; nanomaterials
Most frequent Subject Category	Benavides-Mendoza, Adalberto (Universidad Autonóma Agraria Antonio Narro-UAAAN); Juárez-Maldonado, Antonio (Universidad Autónoma Agraria Antonio Narro-UAAAN); Cadenas-Pliego, Gregorio (Centro de Investigación en Química Aplicada-CIQA); Fernández-Luqueño, Fabian (Centro de Investigación y de Estudios Avanzados-CINVESTAV SALTILLO); Iqbal-Hafiz, M.N. (Tecnológico de Monterrey)
Single-authors docs	2
Co-Authors per Doc	6.36
International co-authorships %	36.44
Average citations per doc	30.63
Most local cited documents	Tapia-Hernández *et al.,* 2015, (141); López-Vargas *et al.,* 2018, (108); García-López *et al.,* 2019, (89); Hernández-Hernández *et al.,* 2018, (62); García-López *et al.,* 2018, (61).
Most cited authors	Iqbal-Hafiz, M.N. (1016): Bilal, M. (887); Cadenas-Pliego, G. (709); Benavides-Mendoza, A (627); Juárez-Maldonado, A. (558)

In the studied region, 72.7% of the papers are classified as articles, 18.7% as reviews and the rest as book chapters, letters to the editor and conference proceedings. The papers identified were published in 161 journal titles. This high number indicates an enormous dispersion in the channels of scientific communication and a wide variety of approaches to the analysis of NT applied to agriculture. The journals that accumulated the most papers are, Molecules with 7 papers, followed by Notulae Botanicae Horti Agrobotanici Cluj-Napoca with 6 papers, Chemosphere 5 papers and International Journal of Biological Macromolecules 4 papers.

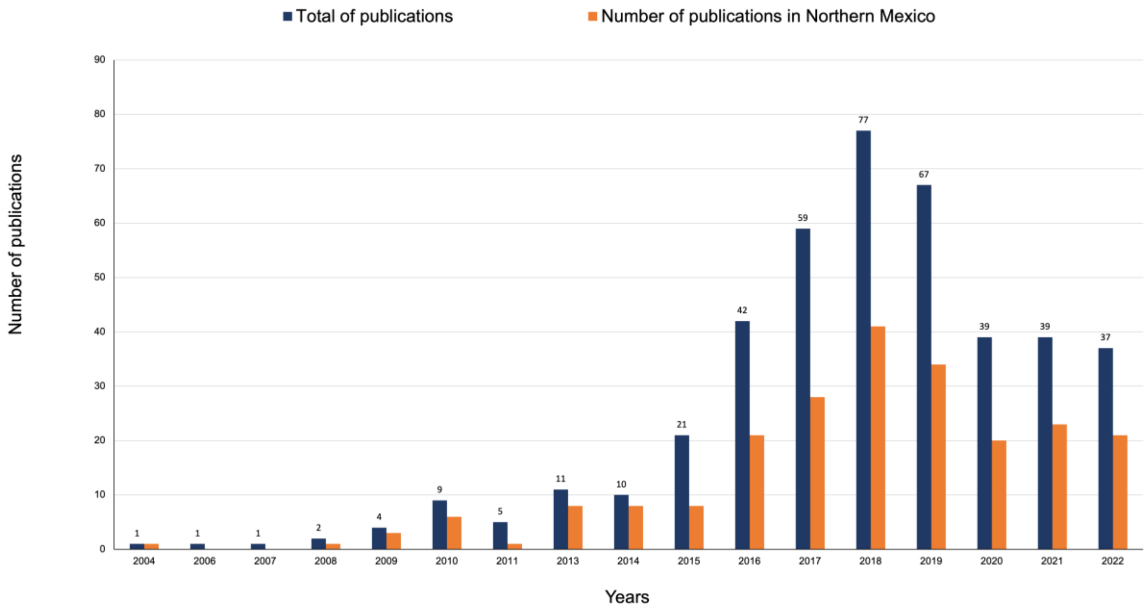

Figure 1. Publications by year in the field of nanotechnology applied in agriculture. The bars in blue indicate the total number of papers and the bars in orange indicate the northern states publications.

The figure 2 shows three aspects of scientific production, a) the geographic distribution of publications in the area of study, b) the main academic institutions and c) the foreign institutions with the greater scientific collaboration (number of co-authorships). In terms of the States, the largest number of papers is found in Coahuila, Sonora, and Nuevo Leon; together, these entities accumulate slightly more than half of the scientific production in the subject. The three academic institutions with the highest number of papers are the Universidad Autónoma Agraria Antonio Narro (UAAAN), the Universidad of Sonora (UNISON) and Centro of Investigación in Química Aplicada (CIQA). Regarding scientific collaboration, all the papers are co-authored and 34% of them have at least one international collaboration. The countries with which the authors from the country's northern region have the greater collaboration are the United States of America and China (68 and 19 papers, respectively). They are followed by India (13), Brazil (9), Italy (9) and Spain (7). The collaboration with China is expected to continue to grow as it is the country with the highest scientific production in nanotechnology. South Korea is also boosting scientific production in agro nano (Parisi *et al.,* 2014).

As for collaboration with foreign institutions, the most frequent relationships are with the University of El Paso Texas (20 papers), University of Houston (9 papers), University of Puerto Rico Rio campus Piedras (7 papers) and University of California Los Angeles (6 papers).

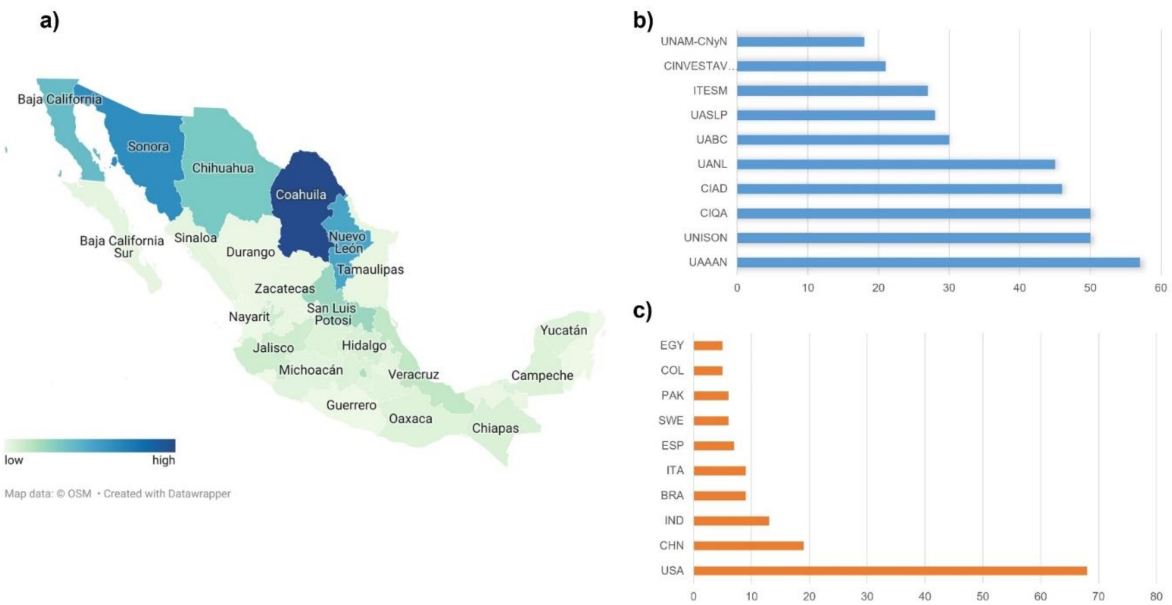

Figure 2. a) Geographical distribution of scientific production b) Main institutions in Mexico c) Main countries of collaboration. Map created with Datawrapper.

The figure 3 shows a cloud of author keywords most cited in the documents. The figure was generated using the frequency of author keywords of the papers published in institutions in northern Mexico. This visualization allows us to map the topics of greater interest to academics in the studied region, types of nanomaterials, applications, among others. If we exclude the terms that appear determined by the search strategy such as "nanotechnology", "nanoparticles" and "nanomaterials", and others related to agriculture and food stand out, such as pesticides, nanofertilizers, germination, morphology, among others.

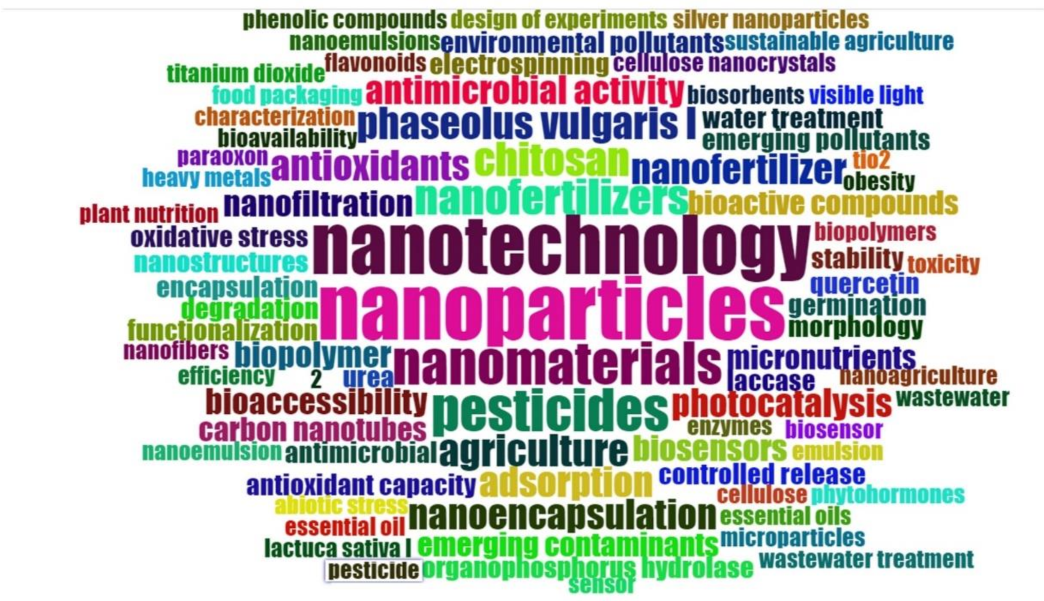

Figure 3. Author keyword cloud. Created with Biblioshiny.

Agronanotechnology and its vision as a line of research in Mexico

The nanotechnology (NT) is a branch of science devoted to studying and manipulating matter at the scale of atoms and molecules. The main objective of NT is to achieve the controlled assembly of atoms to form nanoparticles (NPs) and produce materials that, at the microscale, present different or improved properties (Elmer and White, 2018). Currently, NT drives innovation in various sectors such as telecommunications, electronics, cosmetics, textiles, and medicine, creating products and applications such as high-speed microchips of tiny size, to the creation of new vaccines against COVID-19 (Ortega-Berlanga *et al.,* 2020; Palestino *et al.,* 2020).

The agronanotechnology is expected to be one of the fastest-growing disciplines (Elmer and White, 2018). It is an emerging and multidisciplinary field that deals with developing and applying nanomaterials in the agricultural sector. Its main characteristic is generating organic, inorganic, or hybrid (mixture of both) NPs, used as the main active compound or vehicles to transport biomolecules (Tejeda-Villagómez *et al.,* 2022). Their constant development has allowed the creation of a wide variety of products and systems that are used for the transport and release of nutrients, improvement of packaging, and development of nanosensors, nanofertilizers, antimicrobial agents, nanopesticides, nanoherbicides, nanofungicides, among others (Chhipa, 2019; Anzaldo and Hernandez, 2020; Bhandari *et al.,* 2023). Additionally, there is a growing interest in the application of agronanotechnology to provide viable alternatives to the excessive use of agrochemicals and antibiotics, which have seriously deteriorated crop soils and induced the formation of more virulent and resistant pathogens (Wu *et al.,* 2023).

The development of NT and its different applications is due to the intimate participation of physics, chemistry, and biology (Hernández-Adame *et al.,* 2019a). On the other hand, in the case of agronanotechnology, the participation of agricultural sciences and social sciences becomes necessary to orient innovations to consider cultural, economic, and environmental aspects at early stages of research. These interdisciplinary collaboration exercises have been carried out for some time in other countries. However, they are still far from being popular among decision-makers, managers, or scientists in Mexico. The early stage of agronanotechnology development represents an opportunity for innovation processes to be more open. It can serve as the starting point to identify the lines of research cultivated in academic institutions and begin to elucidate mechanisms of social orientation of research agendas, aspects to which this work seeks to contribute.

Nanoparticles with potential use in phytosanitary control

The nanoscience aims to be a platform for developing low-cost, efficient, and environmentally friendly agricultural products. In this sense, using nanomaterials has proven to be an effective alternative to reduce or eliminate the excessive use of chemicals or biological agents for phytosanitary control (Basavegowda and Baek, 2021). The literature shows that NPs based on oxides, metals, metalloids, carbon, quantum dots, biopolymers, or liposomes, have been evaluated in developing phytosanitary formulations (Worrall *et al.,* 2018). A compilation of the most commonly used nanomaterials in agriculture is presented in Table 4, where the main characteristics of each nanomaterial are described along with their potential for use in plant pathology or other agricultural benefits.

Of the wide variety of nanomaterials available, formulations based on Ag, Cu, TiO_2, ZnO, and Al_2O_3 NPs are the most widely used. These systems have shown high antimicrobial activity against a wide variety of pathogenic microorganisms, including *Podosphaera xanthii* (Hafez *et al.,* 2020), *Sphaerotheca pannosa* (Burketová *et al.,* 2022), *Colletotrichum musae*), *Bipolaris sorokiniana*, *Phytophthora parasitica*, *Fusarium* spp. (Li *et al.,* 2021), or *Meloidogyne* spp. (Khan *et al.,* 2022), among others. Likewise, foliar, stem, and root inoculation have been evaluated, demonstrating that these systems can be absorbed by different parts of the plants and increase their effectiveness in pathogen control or plant growth, as has been observed in *Solanum lycopersicum* (Ahmed *et al.,* 2023), *Zea maize* (Francis *et al.,* 2022), *Phaseolus vulgaris* (Ponce-Garcia *et al.,* 2022), *Glycine*

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max (Yusefi-Tanha *et al.,* 2022), *Cucumis sativus* (Gupta *et al.,* 2022), *Mangifera indica* (Muhammad *et al.,* 2022) and other crops.

Table 4. Types of nanoparticles with potential use in plant pathology.

Nanoparticles (NPs)	Main characteristics	Applications	References
Biopolymers based on sugar, starch, cellulose, collagen, gelatin, silk fibroin	Organic NPs-based on covalently linked natural polymers. Its shape might be spherical or without a definite form. Its size depends on the molecular weight of the macromolecule and ranges from 20 to 1000 nm.	Transport agents for the administration of drugs and antimicrobial agents	Tariq *et al.,* 2023
Dendrimers	Biopolymer-based NPs covalently bound by a core and radial growth to form a sphere.	Delivery vehicles for drugs, gene products and antimicrobials	Chauhan *et al.,* 2020
Liposomes	Arrangement of phospholipids in a spherical shape with the ability to encapsulate water-soluble compounds		Worrall *et al.,* 2018
Graphene and Graphene oxide	Sheets	Antimicrobial agents, transport vehicles for delivery of nutrients and genetic material	Ali *et al.,* 2017; Pan *et al.,* 2016; Zhao *et al.,* 2011
Single-walled or multi-walled carbon nanotubes	Single or multi-walled nanotube		Prasad *et al.,* 2014; Lahiani *et al.,* 2013
Metals and metal oxides	NPs synthesized in different shapes as cubes, spheres, rods, and sheets with sizes less than 100 nm and usually with modified surface chemistry.	They are used as bactericides, fungicides, nano-fertilizers, transport vehicles for antimicrobial agents, nutrients, and genetic material.	Rizwan *et al.,* 2019; Vanti *et al.,* 2019; Wang *et al.,* 2020

In addition, it has been demonstrated that extracts of cacti and their fruits rich in active compounds such as *Stenocereus queretaroensis* (Padilla-Camberos *et al.,* 2021) or *Opuntia ficus* (Silva-de-Hoyos *et al*., 2012), present high reducing capacity to synthesize NPs with antimicrobial potential. This fact opens an opportunity for new applications of products produced in the arid zones of Mexico (Worrall *et al.,* 2018).

Agricultural nanosensors

The nanosensors are another rapidly growing field of agronanotechnology. These devices consist of biological components such as receptors, enzymes, antibodies, nucleic acids, and microorganisms connected to an NP and a transducer to generate an output or signal that humans can use (Kang *et al.,* 2010). The nanosensors help in real-time tracking of crop health and progression by collecting accurate information regarding moisture content, soil fertility, presence of pathogens, nutrient monitoring, onset of plant diseases, residual agrochemicals, etc. (Duhan *et al.,* 2017; Raliya *et al*., 2017). The information provided by nanosensors enables timely decision-making to increase the quality and quantity of agricultural products. The literature reports, for example, the development of nanosensors to monitor the presence of pathogens (Srivastava *et al*., 2018) and to estimate nitrogen uptake in crops (Beegum *et al*., 2022), or when the disease progresses and begins to spread through different parts of the crop (John *et al*., 2022). Ali *et al*., (2017) who has used this technology, shows remarkable improvements in crop yields and efficient use of inputs, translating into economic gains and reducing soil stress. Likewise, nanosensors have been developed to monitor nutrients in crops, thus being able to effectively determine the period and number of agrochemicals to be used based on crop needs (Beegum *et al*., 2022). These data have helped to develop other technological platforms, such as precision agriculture.

The different nanoparticles based on oxides, metals, polymers, quantum dots, and carbon structures have been used to develop nanosensors. The table 5 shows a compilation of the development of nanomaterials used as nanosensors and the target molecule, where the detected compounds or microorganisms (agrochemicals, bacteria, etc.) from the agricultural sector are shown (Chhipa, 2019).

Table 5. Nanoparticles used in the development of nanosensors for the agricultural sector

Nanoparticle (NPs)	Agrochemical or interest compound detected	Reference
ZnO-chitosan	*Trichoderma harzianum*	Siddiquee *et al*., 2014
Titanium dioxide (TiO_2)	Atrazina (herbicide)	Yu *et al*., 2010
Graphene oxide	Nitrates	Pan *et al*., 2016
Graphene	Herbicide detection	Zhao *et al*., 2011
Multi-walled Carbon Nanotubes	Glyphosate and glufosinate (herbicides)	Prasad *et al*., 2014
PEDOT Nanofibers	Nitrates	Ali *et al*., 2017
AuNps	Acetamiprid (insecticide)	Shi *et al*., 2013
	Urea and urease activity	Deng *et al*., 2016
	Pantoea *stewartii sbusp*. (bacterium)	Zhao *et al*., 2014a; Y. Zhao *et al*., 2014b
	Organophosphate (pesticides)	Kang *et al*., 2010
	Cymbidium mosaic virus (CymMV) and *Odontoglossum ringspot virus* (ORSV)	Lin *et al*., 2014
AgNps	Herbicide detection	Dubas and Pimpan, 2008
Quantum dots	DNA detection	Bakhori *et al*., 2013

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Nanofertilizers

A nanofertilizer is a nanomaterial that can either be a plant nutrient or a carrier of a plant nutrient. They are used to increase soil fertility, plant nutrient bioavailability, and product quality. Many nanoparticles are currently used as nanofertilizers among which carbon nanotubes, ZnO, TiO_2, AgNPs, CuO, FeS_2, and SiO_2 stand out. Compared to synthetic fertilizers, nanomaterials' objectives are slow degradation and better biodistribution that allows releasing nutrients efficiently within the plant (Qureshi *et al.,* 2018). This can benefit crops because adequate fertilization periods of up to 5 times longer can be achieved compared to synthetic fertilizers (Subramanian *et al*., 2015). Concerning the method of administration, the literature reports several studies concerning doses, treatment periods, and modes of application for many crops. For example, Faizan *et al*. (2018), evaluated different concentrations of ZnO in tomato plants; their results showed that these NPs induce an increase in parameters related to plant height, root length, fruit weight, chlorophyll, photosynthetic rate, protein content, lycopene, β-carotene, fruit number, yield, gas exchange by leaves, and increase in the mRNA expression level of SOD and GPX genes that induce plant resistance to salinity (Alharby *et al*., 2016; Faizan *et al*., 2018). A compilation of the most used nanomaterials in crops of agricultural interest produced in arid zones and some produced in non-arid areas are shown in Table 6. In addition, the doses, mode of application, and beneficial effects are described.

Table 6. Different types of nanoparticles used as nanofertilizers, dosage used, treatment time and response.

Nanomaterial as fertilizer	Crops	Main results	References
Multi-walled carbon nanotubes	*Hordeum vulgare, Glycine max, Zea mays, Triticum aestivum, Zea mays, Arachis hypogaea, Allium sativum growth enhancement*	The nanotubes induce increased germination, seedling growth, water uptake, and biomass accumulation.	Lahiani *et al*., 2013
Nanohydroxyapatite nanoparticles (HA-NPs) with triple superphosphate (TSP)	Soybean (*Glycine max*)	The HA-NPs were effective at supplying P, with application of the nanoparticles increas(ing) the growth rate and seed yield by 32.6 and 20.4%	Liu and Lal, 2014
P-doped nanoFerrihydrite nanoparticles (P-nFh)	Rice	P-nFh uptake rates were like the P administered as phosphate. The results show positive effect on plant growth.	Bollyn *et al*., 2019
ZnO NPs	*Coffea arabica*	Increase in the rate of photosynthesis and biomass.	Rossi *et al*., 2019
	Triticum aestivum	Higher grain yield and biomass accumulation.	Du *et al*., 2019

Nanomaterial as fertilizer	Crops	Main results	References
	Nicotiana tabacum	Improvement of plant growth, enzymatic activities, and anatomical properties of plants.	Raliya and Tarafdar, 2013
	Cyamopsis tetragonoloba	Positive effect on growth physiology, improvement in biomass accumulation, and nutrient concentration.	
FeS_2 NPs	*Cicer arietinum; Pinacia oleracea; Daucus carota; Brassica juncea and Sesamum indicum*	Increase in germination and yield.	Das *et al*., 2016
CuO NPs	*Spinacia oleracea*	Improvement in photosynthesis	Wang *et al*., 2020
	Solanum lycopersicum	Induce resistance to different diseases.	Giannousi *et al*., 2013
Fe/SiO_2 NPs	*Arachis hypogaea, Zea mays*	Increased plant growth and biomass accumulation	Najafi *et al*., 2017
Al_2O_3 NPs	*Solanum lycopersicum*	Induce resistance to *Fusarium* spp.	Shenashen *et al*., 2017
TiO_2 NPs	*Spinacia oleracea*	Induce higher accumulation of biomass, chlorophyll, nitrogen, and protein content.	Yang *et al*., 2007
AgNPs	*Triticum aestivum*	Growth inducers and tolerance to heat stress.	Iqbal *et al*., 2019
	Vigna sinensis	Improves root nodulation and soil microbial diversity.	Pallavi *et al*., 2016
	Vigna unguiculata	Resistance to bacteria *X. axonopodis pv. malvacearum*	Vanti *et al*., 2019
TiO_2 y SiO_2	*Oryza sativa*	Growth enhancement	Rizwan *et al*., 2019

Potential risks to human health and the environment

A pressing concern is the potential risks of agronanotechnology products on the environment and human health. The toxicology suggested that emphasis should be placed on the care of the synthesis processes and the use of NPs. However, the fact that the standard model of research activities is separated from the value-adding stages and commercialization generally carried out in private companies hinders the multidisciplinary analysis necessary to anticipate and limit the undesired or unexpected consequences of the constant use of nanomaterials in agriculture, nor in all the sectors and commercial areas in which they are already being used (Anzaldo and Hernández, 2020). For example, metallic NPs and their derivatives are usually produced by chemical synthesis, which sometimes involves using highly toxic agents or generating harmful by-products. In this sense, green chemistry synthesis or using natural agents to reduce and stabilize

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NPs can be an alternative to reduce the toxicity and negative impact of excessive use of NPs or high doses. However, their low yield in producing the same NPs and poor ability to induce the formation of NPs with defined shapes and sizes have made their application impractical (Ying *et al*., 2022).

On the other hand, it is important to have studies on the monitoring, biodistribution, bioaccumulation, and degradation of metal NPs and their derivatives in different farming systems because the constant use of NPs in agricultural soils can emulate the serious contamination problem of agrochemicals; since, over time, their continuous use can increase the concentration of NPs in soils and water, degrading ecosystems (Wu *et al*., 2023). The responsible use of nanotechnology is a key factor in the care of the environment and human health. The use of organic NPs, the main characteristics of which are biodegradability, biocompatibility, and zero toxicity, is undoubtedly the most promising alternative.

The research centers and public and private universities in Mexico have hygiene and safety commissions that follow strict protocols to monitor the correct use of nanomaterials and their wastes. In Mexico lacks a roadmap to plan and regulate the development of NT in its multi-sectorial diversity. However, there is a specific instance that addresses the advances in international standardization, namely, the Technical Committee ISO/TC 229 Nanotechnologies of the International Standard Organization (ISO). Since 2013, the Mexican government created the Technical Committee for National Standardization in Nanotechnologies (CTNNN) coordinated by the National Metrology Center (CENAM), which has as its main functions to attend the standardization work of ISO/TC 229 and develop national application standards on the subject (CENAM, n.d.). The CTNNN has published 19 standards on terminology, nomenclature, measurement, and characterization of nanomaterials' physical, chemical, and toxicological properties (SINEC, n.d.).

In terms of environmental and health protection, five standards have been published that address protocols on occupational risk and recommendations for labeling products containing nanomaterials (Table 7). There is currently a lack of a specific regulatory framework for commercial applications of agronanotechnology, which constitutes a pending agenda for the future of this technology in Mexico. To address the concerns of academic institutions, industry and consumers about compliance with quality standards and toxicity aspects in terms of health and the environment, specific regulatory mechanisms are needed to guide the actors' decisions along the production chain, including decisions about what to research or which products to finance. For example, in Mexico, there is a need to develop adequate protocols to evaluate the efficiency and safety of nanomaterials in plants or soil, since there is a local circulation of agronano products from other countries.

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Table 7. Standards for nanotechnologies in Mexico related to socio-environmental issues

Date of Publication in the Federal Official Gazette	Standard	Scope
February 01, 2017	NMX-R-12901-1-Occupational risk management applied to engineered nanomaterials Part 1: Principles and approaches.	Provides guidance on safety measures related to manufactured nanomaterials, including the use of engineering controls and personal protective equipment, guidance on the control of accidental spills and releases, and the proper handling of these materials in their disposal.
September 25, 2019	NMX-R-12901-2- Occupational risk management applied to engineered nanomaterials Part 2: Use of the control banding approach	Describes the use of a banded control approach for the control of risks associated with occupational exposures for nano-objects, and their aggregates and agglomerates larger than 100 nm (NOAA), even if knowledge related to their toxicity and quantitative exposure estimates is limited or non-existent.
June 3, 2020	NMX-R-13121 Nanomaterial risk evaluation	Describes a process for identifying, assessing, addressing, making decisions about, and communicating potential risks from the development and use of manufactured nanomaterials, in order to protect the health and safety of the public, consumers, workers, and the environment.
August 11, 2015	NMX-R-13830 Guidance on voluntary labelling for consumer products containing manufactured nano-objects	Provides guidance on the format and content of voluntary labeling for manufactured nano-objects and products, preparations and mixtures containing manufactured nano-objects.
June 03, 2020	NMX-R-16197 Compilation and description of toxicological screening methods for manufactured nanomaterials	It provides a compilation and description of in vitro and in vivo methods that may be useful for toxicological screening of manufactured nanomaterials.

Source: Data from Sistema Integral de Normas y Evaluación de la Conformidad del Gobierno de México.

Research agenda in agronanotechnology in the arid zones of Mexico

According to the present bibliometric analysis, sixteen crops of importance for agronanotechnology research were found; the most studied is *Solanum lycopersicum* L. (12 papers), followed by green beans (*Phaseolus vulgaris* L.) (3 papers), *Persea americana* Miller (2 papers) and habanero chile (*Capsicum chinense*) (2 papers). Concerning cacti and their derivatives, it is important to highlight the need for more participation of the scientific community in this field, despite the importance of

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these products since they can only be produced in these arid regions of the country. The table 8 show the most recent published works according to the crop type.

Table 8. Selection of articles on crops of major interest for agronanotechnology in the arid zones of Northern Mexico.

Crop	Title	Type of Nanomaterial	Author(s)	Year
Lettuce plants (*Lactuca sativa* L.)	Impact of $ZnSO_4$ and ZnO nanoparticles on seed germination and seedling growth on lettuce.	$ZnSO_4$ and ZnO Nanoparticles	Benavides-Mendoza *et al*.	2023
Tomato (*Solanum lycopersicum* L.)	Effect of carbon-based nanomaterials on Fusarium wilt in Tomato.	Carbon-based nano materials	González-Garcia *et al.*	2022
Lettuce leaves (*Lactuca sativa* L.)	Commercial and phytochemical quality in biofortified orejona lettuce with zinc oxide nanoparticles.	NPsZnO	Fortis-Hernandez *et al.*	2022
Apple fruits (*Malus domestica* L.)	Effects of edaphic fertilization and foliar application of Se and Zn nanoparticles on yield and bioactive compounds in apple.	NPs of Se and Zn	Montaño-Herrera *et al.*	2022
Tomato (*Solanum lycopersicum* L.)	Gas exchange parameters, fruit yield, quality, and nutrient status in tomato are stimulated by ZnO nanoparticles of modified surface and morphology and their application form.	ZnO	Pérez-Velasco *et al.*	2021
Green beans (*Phaseolus vulgaris* L.)	Efficiency of foliar application of zinc oxide nanoparticles versus zinc nitrate complexed with chitosan on nitrogen assimilation, photosynthetic activity, and production of green beans.	ZnO nanoparticles complexed with chitosan	Palacio-Márquez *et al.*	2021
Avocado (*Persea americana Miller*)	*In-vitro* evaluation of copper nanoparticles as a potential control agent against the fungal symbionts of the invasive ambrosia beetle *Euwallacea fornicates.*	CuNPs	Cruz *et al.*	2021
Vanilla (*Vanilla planifolia*)	Silver nanoparticles affect the micropropagation of vanilla.	AgNPs	Pastelín-Solano *et al.*	2020
Sweet potato plants	Effect of copper oxide nanoparticles on two varieties of sweetpotato plants.	CuNPs	Bonilla-Bird *et al.*	2020
Habanero papers (*Capsicum chinense)*	Foliar Application of Zinc Oxide nanoparticles and Zinc Sulfate boosts the content of bioactive compounds in habanero peppers.	ZnO, ZnSO4	García-López *et al.*	2019

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Crop	Title	Type of Nanomaterial	Author(s)	Year
Fishes	Immobilizing yeast beta-glucan on zinc-layered hydroxide nanoparticle improves innate immune response in fish leukocytes.	Zinc-layered hydroxide nanoparticle	Angulo *et al.*	2018
Pepper (*Capsicum annuum* L.)	Zinc Oxide Nanoparticles boosts phenolic compounds and antioxidant activity of pepper during germination.	ZnO	García-López *et al.*	2018
Pea (*Pisum sativum*)	Copper oxide nanoparticles and bulk copper oxide, combined with indole-3-acetic acid, alter aluminum, boron, and iron in Pea seeds.	CuNPs	Ochoa *et al.*	2018
Wheat	Toxicity assessment of cobalt ferrite nanoparticles on wheat plants.	Cobalt ferrite nanoparticles	López–Luna *et al.*	2018

Challenges and trends

From the data analysis presented here, it is possible to affirm that agronanotechnology has allowed the development of novel systems used in the agricultural sector; however, we must recognize that this line of research has yet to reach its maturity stage. The critical issues and challenges related to the biodistribution, degradation, and biosafety of nanomaterials used in soils and agricultural systems still need further study. This fact opens different niches of opportunity, ranging from focusing future efforts to produce multifunctional nanomaterials on a large scale by friendlier methods to the production of fully biodegradable and biocompatible nanomaterials to mitigate their accumulation and environmental impact (Hernández-Adame *et al.,* 2019b). An alternative may be the generation of multifunctional nanomaterials that can reduce the growth of pathogenic microorganisms and, at the same time, serve as fertilizers for the crop. Regarding degradation and to avoid bioaccumulation, possibly the use of biodegradable biopolymers or natural products based on chitosan, gelatin, polylactic acid, β-glucans, or bioplastics based on starch or cellulose can serve as structural matrices in the elaboration of NPs that can be naturally degraded by enzymes or oxidation-reduction processes (Moussout *et al.,* 2016). On the other hand, it is expected that new scaling-up methods in the production of NPs will make it possible to integrate new NPs-based systems into the portfolio of agricultural products that serve as an alternative for reducing the use of agrochemicals, developing new packaging for storing and distributing food, developing nanosensors, nanovaccines, nanopesticides, resistance inducers, soil improvers, and nanofertilizers.

Moreover, it is important to monitor and guide this technology's trajectory by governance approaches that assume as a starting point that the uses of sciences and technology are not neutral. Approaches that consider the current moment humanity is facing are characterized by the emergence of natural and manufactured risks. This requires that all actors involved in knowledge production assume that the problems we pose are in contexts of *post-normal science,* where facts are uncertain, values are in dispute, and the stakes are high. Hence, decisions are urgent (Funtowicz and Ravetz, 2000).

Based on these premises, trends in the governance of agri-nanotechnology could revolve around two thematic clusters. The first is the governance of regulation, which implies advancing the analysis of risks to human health and the environment, as well as the social effects on the food production cycle. It is a reality that governments and companies allocate very few resources to identify and assess risks. Consequently, more elements to implement some regulations are needed. In this regard, an interesting work is that of the research routes proposed in the European Environment Agency report "Late lessons from early warnings: Science, precaution, innovation" (Gee *et al*., 2013), which classifies NTs as an emerging risk and warns of the need to use the precautionary approach. Another report is that of the International Risk Governance Council (IRG), which in 2008 published a risk analysis on the use of nanomaterials in food and cosmetics, proposing a path of incremental regulations based on the precautionary principle. Both reports and their recommendations are still valid.

The second thematic cluster is the *governance of technology promotion*. Along these lines, there is a clear need for further inquiry into how to orient agronanotechnology to the needs of smallholder food systems. According to the Committee on World Food Security, smallholders provide 70% of global food production and, paradoxically, suffer food insecurity (CFS, 2015).

From the bibliometric point of view and based on the data presented for the case of Mexico, scientific production in agronanotechnology is still incipient. However, the linear trend in the production growth suggests that there will be an increase in publications. It is impossible to predict the direction it will take since the dispersion of the titles of the journals where this line of work is published still associates the authors with their disciplines of origin. However, it is likely that in terms of the application types, it will continue to add to research in food and agriculture. The high concentration in the geographical distribution of capabilities is not surprising since this is a characteristic of scientific activity in Mexico in all disciplines. What is interesting is the forms of collaboration that agronanotechnology is shaping, where, as it was shown, there were no published works of individual authorship. Also, it can be seen that collaboration between Mexican institutions prevails over international collaboration.

Conclusions

In Mexico, food production is becoming increasingly difficult due to problems related to climate change, overpopulation, decreasing fertile land, and increasingly restricted access to fresh water. NT can be an alternative to address these challenges. As have been shown in this study, this science offers potential benefits to the agricultural sector with the innovation of nanoparticle-based systems for use as pathogen control agents, nanosensors, or nanofertilizers, among many other applications. In Mexico, there are specific research capabilities, and that experimental work is being carried out taking advantage of the infrastructure in some entities of the republic. The focus is mainly on crops of interest to the agricultural export sector, such as tequila, tomato, avocado, some types of chili, and fruits such as watermelon. It was also found that there is an interest in some work that addresses the toxicological aspects of the NPs in agri-food systems. In this sense, it would be necessary to explore with producers of other crops in the region what problems they are facing and consider cacti and their derivatives within the research agendas since they have important commercial, health, and nutritional value.

The technology alone is not enough and is necessary to consider the pre-existing inequalities in rural areas, the social consequences, and the effects on biodiversity. The promotion of agronanotechnology in the country requires, therefore, funding for the identification and evaluation of risks, the generation of regulations for products currently on the market, the creation of transdisciplinary work networks that involve groups related to toxicology, ecology, the governmental sector, social sciences, and agricultural producers. In addition, it requires a better understanding of how global food production works in a regime characterized by the co-optation of technology by large agri-food consortiums. In this sense, two of the authors of this paper participate in the National Technical Committee for Standardization in Nanotechnologies, and from there, we seek to collaborate in the responsible governance of this technology.

Ethics statement

Not applicable

Consent for publication

Not applicable

Availability of supporting data

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

Funding

Not applicable

Author contributions

Conceptualization, L.H.A. and M.A.M; formal analysis, L.H.A., M.A.M., Y.I.H.G. and L.G.H.M.; investigation, L.H.A, MAM and Y.I.H.G; writing—original draft preparation, L.H.A., M.A.M., Y.I.H.G and L.G.H.M.; writing—review and editing, L.H.A., M.A.M. and Y.I.H.G; supervision, L.H.A.; project administration, M.A.M and L.H.A.

Acknowledgments

Mónica Anzaldo Montoya acknowledges to CONAHCYT's Frontier Science Project No. 304320. Luis Hernandez-Adame acknowledges to CONAHCYT's project No. 316934.

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