

Mexican Bacterial Biofertilizer Program of INIFAP

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ABSTRACT

In 1998, the considerable reduction in agricultural profitability, as a consequence of the rise in prices of agricultural inputs —particularly chemical fertilizers and pesticides—, prompted the Mexican government to seek production alternatives to reduce the use of agrochemicals in the country. Given the importance of food self-sufficiency and the profitability of national agricultural activity, the National Institute of Forestry, Agriculture, and Livestock Research (INIFAP) of Mexico launched the ‘Programa de Investigación sobre Biofertilizantes’. Since 1999, the initiative has had the uninterrupted support of the Mexican Secretariat of Agriculture and Rural Development (SAGARPA) to generate national technologies for the development and management of biofertilizers and to promote their use among agricultural producers. As a starting point, INIFAP sought to consolidate alliances with some of the Mexican leading research institutions, in order to promote the use of biofertilizers as an alternative to chemical fertilizers. During this first phase, microorganisms —such as *Glomus intraradices*, *Bradyrhizobium japonicum*, *Azospirillum brasilense*, and *Rhizobium etli*— were used to reduce the doses of chemical fertilizers in some of the main domestic staple crops. Given the success of this first phase, INIFAP established mycorrhizal production centers in different regions of the country and then a team of INIFAP scientists from various fields of science was integrated. Initially, this team focused on plant growth-promoting bacteria, as well as on the development and formulation of new and more efficient bacterial biofertilizers, using local strains from the main agro-ecological zones of Mexico. Later on, they focused on technology transfer and the training of Mexican producers to apply and use the products. This review describes some of the main achievements accomplished by the INIFAP Biofertilizer team, particularly in the area of bacterial bioproducts.

Keywords: biofertilizer, bioinoculant, *Azospirillum*, *Pseudomonas*, *Bacillus*.

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INTRODUCTION

The use of chemical fertilizers decreased during the early 1990s. However, a growing trend for their reincorporation in agriculture —to the levels recorded during the 1980s (Ávila, 2001)— led the Mexican government to seek for alternatives that increase profitability,



while reducing the use of chemical fertilizers. For this purpose, three technologies were considered: a) The utilization of organic fertilizers—including manure, compost, compost tea, bioles (fermented liquid biofertilizers), and vermicompost— b) The determination of the optimal fertilization doses based on soil analysis, and c) The use of microorganisms capable of promoting plant growth and reducing the use of synthetic fertilizers without impacting crop productivity. After INIFAP successfully validated in 1999 the use of microorganisms such as *Glomus intraradices*, *Bradyrhizobium japonicum*, *Azospirillum brasilense*, and *Rhizobium etli* as a viable alternative to reduce the use of chemical fertilizers, various mycorrhiza production centers were established to meet the growing bioinputs demand of Mexican producers.

In 2007, Dr. Gerardo Armando Aguado Santacruz—researcher at the Bajío Experimental Field in Celaya, Guanajuato— took over the leadership of the Programa Nacional de Investigación de Biofertilizantes of INIFAP. At the beginning, the biofertilizer research team proposed the isolation of plant-growth-promoting bacteria that could complement the beneficial effects of the mycorrhiza produced by INIFAP. The potential of these bacteria, known as plant-growth-promoting rhizobacteria (PGPR), for reducing the chemical fertilization doses applied to crops has been scientifically proven during the last 20 years. Besides, In addition, the society is now aware of the importance of consuming healthier food while minimizing the environmental impact caused by the use of agrochemical products.

Biofertilizers—also known as bioinoculants, microbial inoculants, or soil inoculants—are agro-biotechnological products containing active/dormant microorganisms (bacteria or fungi, alone or in combination) that are added to crops for stimulating their growth and productivity (Aguado-Santacruz *et al.*, 2012). Although the term “biofertilizer” was initially used to facilitate the registration of strains for commercial purposes, some authors point out that the term is not completely correct, because only a few microorganisms can strictly fulfill the specific function of incorporating new nutrients into ecosystems—mainly nitrogen-fixing microorganisms (Bashan, 1998). In recent decades, several studies have focused on the role of growth-promoting bacteria in plants, proving their beneficial effects on crop productivity and health. Rhizosphere bacteria that aggressively colonize plant roots are known as rhizobacteria, while, bacteria that can also stimulate plant growth are commonly known as plant-growth-promoting rhizobacteria (PGPR). This growth-promoting activity influences various agronomic variables, including germination increase, emergence increase, seedling establishment or vigor, root system proliferation, or plant biomass or final crop yield increase.

Although this concept of PGPR emphasizes the effect of bacteria on plant growth, no less important are the activities that these microorganisms exert on the development of plants, advancing flowering times in ornamental plants or improving the quality of the fruits in terms of their size or organoleptic properties. Some researchers mention, for example, that it is possible to improve the sweetness degree (Brix degrees) of some fruits such as melon, using phosphate-solubilizing bacteria (Chien *et al.*, 2009). On the other hand, the use of biofertilizers has proven that improving maize performance is indeed possible (Fallik and Okon, 1996; Purcino *et al.*, 1996), from the reduction of germination time and

the increase of germination percentages and seedling establishment rates to high final crop yield increases. In addition, it has been stated that 13 to 20% of maize nitrogen content can be attributed to the nitrogen-fixing activities of bacteria such as *Azotobacter* (Soliman and Abdel Monem, 1994). Covarrubias-Ramírez *et al.* (2005) evaluated the kinetics and efficiency of P uptake in potato plants (*Solanum tuberosum* L.) cv. Alfa, using the ^{32}P isotope technique. These researchers reported that inoculation with *Bacillus subtilis* increased potato biomass by 31.7%, and P uptake by 27.5%. They also mention that inoculation of chickpea plants with *Mesorhizobium cicerii* resulted in different beneficial effects on the growth and development of this crop, which allowed a 70% reduction of the recommended dose of nitrogen (urea) without affecting grain yield (2.05 ton ha^{-1}) compared to control plants fertilized with 100 kg N ha^{-1} that produced 1.98 ton ha^{-1} . According to Biswas *et al.* (2000), nitrogen-fixing microorganisms can promote plant growth by transferring fixed nitrogen to plants or by improving nutrient uptake through modulation of the hormonal activity. In this sense, Bashan (1999) pointed out that inoculation with plant-growth-promoting microorganisms (*e.g.*, *Azospirillum* sp.) results in a greater accumulation of nitrogen compounds, through the promotion of more effective nutrient uptake without apparent nitrogen fixation. In contrast, Zakry *et al.* (2012) used the ^{15}N isotope technique and found that up to 89% of the N requirement of oil palm seedlings was supplied by its symbiosis with *Azospirillum*. Likewise, Khurram *et al.* (2012) evaluated the effect of ACC deaminase activity or phosphate solubilizing capacity of *Bacillus* strains, either as a single or dual growth promotion mechanism (strains possessing both capacities). Under axenic conditions, bacterial strains with dual growth-promoting traits had a higher capacity to stimulate wheat growth than strains with a single trait. Similarly, these dual-trait bacterial strains were more effective than single-trait strains under soil conditions (pot experiments) for increasing root weight (up to 3.9-fold) and elongation (up to 3.8-fold), shoot dry weight (up to 37.6%), number of shoots (up to 56%), grain yield (up to 38.5%), and grain P uptake (up to 77.4%) of wheat grown with P applied as diammonium phosphate, rock phosphate, or rock phosphate-enriched compost. An almost similar trend was recorded when the same experiment was repeated under field conditions. The inoculation with rock phosphate-enriched compost recorded growth parameter almost comparable with those obtained by diammonium phosphate. In conclusion, the simultaneous presence of two different growth-promoting bacteria capacities could have an additive effect, not only on wheat growth and yield, but also on P uptake.

Furthermore, several studies report improved nutrient uptake when chemical fertilization is paired with beneficial microorganisms. For example, Sundara *et al.* (2002) found that applying the *Bacillus megatherium* var. *phosphaticum* phosphorus-solubilizing bacterium (PSB) increased P availability in the soil, improving sugarcane growth, yield, and quality. This PSB also reduces the P dose requirement by 25%. In addition, studies reported that, in combination with phosphate rock, *B. megatherium* can save up to 50% of production costs by replacing superphosphate. Young *et al.* (2004) compared the effects on growth of a full chemical fertilization dose vs the effects of a multi-functional biofertilizer treatment (a combination of *Bacillus* sp., *B. subtilis*, *B. erythropolis*, *B. pumilus*, and *P. rubiacearum*) and 50% of the recommended chemical fertilization dose applied on

cabbage and water celery. Compared with the complete chemical fertilization treatment, the biological-chemical treatment recorded a 25% and a 34% increase in cabbage yield and water celery dry matter, respectively, which indicates, that it is possible to save at least 50% of the complete chemical fertilization by adopting a complementary approach that combines multifunctional biofertilizers and lower doses of chemical fertilizers.

Benítez-Noyola (2013) proved that maize plants fertilized with 90 and 180 kg N ha⁻¹ and inoculated with *Paenibacillus polymyxa* extracted 20 to 28% more nitrogen from the soil and produced more grain than plants that were only chemically fertilized. For their part, Das *et al.* (2004) reported a greater nitrogen (N₂) accumulation in cotton, with the combination of a chemical fertilization with *Azotobacter* M4. Likewise, Naveed *et al.* (2008) proved that the grain maize yield can be maintained replacing 87 kg urea ha⁻¹—50% of the full dose of N fertilizer (175 kg ha⁻¹)— with 300 kg ha⁻¹ of an organic compost made from waste fruit and vegetables and enriched with 147 g N fertilizer kg⁻¹ of compost; a basal P and K dose (100 and 50 kg ha⁻¹, respectively) was previously applied to all the plots. However, when the N-enriched compost was inoculated with different *Pseudomonas* strains and then applied to the plots along with 88 kg urea ha⁻¹, a significant maize growth and yield increase (1.1 ton grain ha⁻¹) was recorded over the full N fertilizer dose, being superior to the increase obtained with the the organic fertilizer (0.5 ton grain ha⁻¹). According to these authors, *Pseudomonas fluorescens* strain N3 was particularly effective in promoting growth due to its high root colonization capacity, chitinase activity, and ACC deaminase activity. These characteristics give this strain a greater competitive advantage.

The activity of rhizobacteria with ACC deaminase enhances root growth, as a result of an ethylene synthesis reduction, through hydrolysis of ACC into NH₃ and α -ketobutyrate in the inoculated roots (Shaharoon *et al.*, 2007). These results imply that the organic fertilizer inoculation with ACC deaminase-PGPR could help to develop improved bioproducts that combine the nutritional characteristics of compost and the beneficial activities of rhizobacteria, obtaining synergistic effects on both crop growth and productivity.

Abdullahi *et al.* (2013) studied the effect of using a biofertilizer (containing *Azospirillum* sp. and *Glomus mosseae*) combined with poultry manure on the nutrient uptake and growth of plants and microbial population associated to the sesame cultivation under field conditions. Plant height, number of leaves per plant, number of branches per plant, leaf area, and shoot and root dry biomass were higher in the plants treated with microorganisms and/or poultry manure (individually or combined) than in control plants. The combined application of the biofertilizer and poultry manure (bioorganic treatment) at a rate of 5 ton ha⁻¹ produced plants that achieved the best growth parameters, nutrient content, and N, P, and K uptake. In addition, the largest populations of *Azospirillum* sp. (28.6×10^{-6} CFU g⁻¹ soil) and arbuscular fungi (69.3 spores g⁻¹ soil) were recorded in the bioorganic treatment. According to the authors, the positive growth responses of the inoculated plants could be attributed to increased nutrient supply—especially nitrogen— and growth-promoting hormones provided by *Azospirillum* sp. and to the greater absorption of phosphorus and other nutrients resulting from the mycorrhiza colonization (Zaidi *et al.*, 2004). The greater availability of nutrients reported in that study was either the result of the decomposition of organic manure or the transformation of inorganic substance into available forms produced

by microorganisms. The *Azospirillum* sp. population increase—as well as the increase of the spore density and colonization of *G. mosseae*— could be associated with the application of manure, which is a carbon source for microbes. Table 1 shows direct or indirect promotion of plant growth caused by PGPR (Glick, 1995; Persello-Cartieaux *et al.*, 2003).

Plant growth-promoting bacteria can directly impact plant growth through several mechanisms, including: atmospheric nitrogen fixation, mineral solubilization (*e.g.*, phosphorus and iron), siderophore production (solubilization and iron sequestration), and production of growth regulators (hormones) that improve plant growth during different development stages. The production of growth-promoting substances (auxins, gibberellins, and cytokinins) has been one of the main direct mechanisms used by researchers to explain growth stimulation caused by biofertilizers (García de Salamone *et al.*, 2005). The production of indoleacetic acid (IAA) is one of the most widespread growth-promoting mechanisms in bacteria, particularly in Gram-negative bacteria (Steenhoudt and Vander-Leyden, 2000). The amino acid tryptophan, precursor of this hormone, is one of the most abundant compounds in root exudates (Kamilova *et al.*, 2006). Meanwhile, the IAA hormone can be found in up to 80% of bacteria isolated from the rhizosphere of some plants (Loper and Schroth, 1986). The reduction of ethylene levels in plants is another growth-promoting mechanism linked to hormonal metabolism (Li *et al.*, 2009). Ethylene is a plant hormone that can inhibit root development, limiting the capacity of the plant to absorb nutrients and water. In higher plants, the S-adenosyl-L-methionine (SAM) synthase enzyme catalyzes the conversion of methionine to SAM (Giovannelli *et al.*, 1980). In response to damages, floods, droughts, salinity, and herbicides, the enzyme ACC synthase catalyzes the conversion of SAM into 1-aminocyclopropane-1-carboxylic acid (ACC), the immediate precursor of ethylene. Subsequently, the ACC oxidase enzyme catalyzes the conversion of ACC to ethylene, carbon dioxide, and hydrogen cyanide (John, 1991). Increased ethylene levels in the root delays its growth. Some microorganisms, such as species of genera *Pseudomonas* and *Bacillus*, contain an enzyme called ACC deaminase that hydrolyzes ACC to form ammonia and α -ketobutyrate (Glick *et al.*, 2007), preventing the formation of ethylene. Consequently, when ACC deaminase activity increases, ethylene levels in the plant decrease, and root development clearly increases (Saleem *et al.*, 2007).

Another direct mechanism for growth stimulation is the enzymatic reduction of atmospheric nitrogen (N_2) to ammonium (NH_4), commonly referred to as biological nitrogen fixation (BNF). In some plants, this reductive process takes place in specialized structures (such as the root nodules of legumes) and is catalyzed by the nitrogenase enzyme

Table 1. PGPR Plant-Growth-Promoting Mechanisms.

Direct effects	Indirect effects
Atmospheric nitrogen fixation	Antibiosis
Hormone production	Induction of systemic resistance
Increased Fe availability	Reduction in environmental Fe availability
P solubilization	Competition for ecological niche and nutrients
Reduction of ethylene levels	Parasitism and predation

complex, which consists of two distinct proteins: dinitrogenase (iron-molybdenum protein) and dinitrogenase reductase (iron protein) (Bulen and LeComte, 1966).

Vitamin synthesis is another direct mechanism that has been proposed by researchers, because the production of certain vitamins significantly contributes to the growth-promoting activity of certain microorganisms. For instance, *Pseudomonas fluorescens* strain 267 produces water-soluble B vitamins that stimulate the growth of red clover (*Trifolium pratense*) (Marek-Kozaczuk and Skorupska, 2001). Similarly, some *Azotobacter* and *Azospirillum* strains produce B vitamins that promote rooting capacity and impact microbial populations (Revillas *et al.*, 2000). On the other hand, the production of siderophores, also considered a direct mechanism, involves the synthesis of molecules with a high affinity for iron by various microorganisms and grasses (Neilands, 1995) to increase the bioavailability of this element. Some siderophores produced by different bacteria and fungi include ferrichrome (*Ustilago sphaerogena*), mycobactin (*Mycobacterium* sp.), enterobactin and bacillibactin (*Bacillus subtilis*), ferrioxamine B (*Streptomyces pilosus*), azotobactin (*Azotobacter vinelandii*), pseudobactin (*Pseudomonas* B10), and ornibactin (*Burkholderia cepacia*). *P. fluorescens* produces pyoverdine, a peptide siderophore with high affinity for iron (Madigan and Martinko, 2005).

Phosphate solubilization is another direct mechanism carried out by phosphate-solubilizing bacteria (PSB) which can increase the availability of phosphate for plants. PSB are a beneficial group of bacteria capable of hydrolyzing both organic and inorganic phosphorus from insoluble compounds (Goldstein *et al.*, 2003). These bacteria secrete organic acids and phosphatases to convert insoluble phosphates into soluble monobasic (H_2PO_4^-) and dibasic (HPO_4^-) ions, through a process known as rock phosphate solubilization. PSB can solubilize compounds such as tricalcium phosphate, dicalcium phosphate, hydroxyapatite, and rock phosphate through the production of gluconic and 2-ketogluconic acid, which are well-known phosphate solubilizers. Soil phosphate solubilization increases phosphorus availability and, consequently, phosphorous uptake by plants (Gyaneshwar *et al.*, 2002). Bacteria genera capable of solubilizing phosphates include: *Azotobacter*, *Azospirillum*, *Bacillus*, *Burkholderia*, *Enterobacter*, *Erwinia*, *Flavobacterium*, *Mesorhizobium*, *Micrococcus*, *Pantoea*, *Pseudomonas*, *Rahnella*, *Rhizobium*, *Streptosporangium*, and *Yarrowia* (Paredes-Mendoza and Espinosa-Victoria, 2010).

Indirect growth promotion takes place occurs when PGPRs stimulate growth by improving growth-limiting conditions for plants (Glick *et al.*, 1999). For instance, when bacteria suppress diseases caused by pathogens (Smith *et al.*, 1999), either by producing antagonistic substances (mainly antibiotics), by inducing systemic resistance against pathogens (Glick, 1995) or by competing against pathogens for colonization of plant physical spaces (Dekkers *et al.*, 1998). Similarly, siderophore-producing bacteria use iron for themselves, reducing its availability for other competing microorganisms in the rhizosphere, which limits the growth of their competitors.

Regarding indirect mechanisms, research about the benefits of microbial inoculants extends beyond their capacity to improve plant nutrition because microbial inoculants can also induce systemic acquired resistance (SAR) against various phytopathogenic agents, such as *Blumeria graminis*, *Gaeumannomyces graminis*, *Pseudomonas syringae*, and *Fusarium*

culmorum (Khaosaad *et al.*, 2007; Ramos-Solano *et al.*, 2008). SAR is a globalized resistance response in plants. It takes place after a plant is exposed to a pathogen or a pathogen-derived agent. After an early and localized exposure to certain infectious organisms, SAR activates a whole-plant resistance mechanism against a wide variety of pathogens, including the pathogen responsible for the infection. This phenomenon is known as a broad-spectrum response (Bailey *et al.*, 2006). In order to exert their beneficial effects on plants, growth-promoting microorganisms must be rhizosphere-competent —*i.e.*, they must be able to compete with other microorganisms for the nutrients secreted by the root and for the physical space available in the root. Only a small portion of the root surface is covered by bacteria. The junctions between epidermal cells and the points of initiation of lateral roots are the preferred sites for bacterial growth. Once soil microorganisms colonize plant roots, they occupy spaces and consume nutrients that could otherwise be used by phytopathogen agents (O’Sullivan and O’Gara, 1992).

Siderophore production is a dual mechanism that promotes plant growth: it does not only increase iron availability for plants, but it also contributes to the biological control of plant pathogens. Growth-promoting microorganisms sequester iron from the soil, making it useful for themselves and for plant cells that can assimilate the bacterial siderophore-iron complex. Consequently, they limit the amount of iron available in the soil for other microorganisms (Callanan *et al.*, 1996).

Various plant growth-promoting microorganisms synthesize antibiotics (O’Sullivan and O’Gara, 1992); this mechanism is commonly associated with the capacity of biofertilizers to inhibit phytopathogens (Chet and Inbar, 1994; Whipps, 1997). The capacity of some bacteria to suppress pathogenic fungi depends on their capacity to produce antibiotics, such as pyoluteorin, pyrrolnitrin, phenazine-1-carboxylic acid, and 2,4-diacetylphloroglucinol (Picard, 2000). Bacteria can also inhibit the growth of phytopathogens releasing other compounds such as hydrogen cyanide (HCN) and/or lytic enzymes, which include chitinase, 1,3-glucanase, proteases, and lipases (Friedlander *et al.*, 1993; Chet and Inbar, 1994). Although pectinolytic activities are commonly associated with pathogenic bacteria, some non-pathogenic bacterial species such as *Rhizobium* sp. (Angle, 1986), *Azospirillum* sp. (Tien *et al.*, 1981), *Klebsiella pneumoniae*, *Yersinia* sp. (Chatterjee *et al.*, 1978) and *Frankia* sp. also possess this ability.

Based on the above premises, within the objectives of the National Biofertilizers Program of INIFAP, the initial objective was to isolate bacteria from the different agroecological regions of Mexico that had the capacity to stimulate plant growth. The starting point was the creation of a subproject called “Potencial de bioinoculantes microbianos como una alternativa para reducir costos de fertilización en cultivos básicos de temporal,” which was part of the SAGARPA-supported research megaproject called “Incremento en rendimiento, productividad y eficiencia en el uso de fertilizantes químicos, biológicos y abonos orgánicos de los principales cultivos básicos empleando métodos racionales de diagnóstico y recomendación” (Agreement No. 30333454).

The INI2709 biofertilizer, based on the bacteria *Bacillus subtilis*, *Herbaspirillum frisingense* and *Pseudomonas fluorescens*, was developed through this subprogram. This bioproduct was nationally evaluated in order to increase the profitability of maize grown under rainfed

systems. The results of this research proved the feasibility of reducing at least 30% of the chemical fertilization doses applied to maize in rainfed systems. As a result, the INIFAP Biofertilizer Team earned the Innovación Tecnológica 2008 award, granted by the Science and Technology Council of the State of Guanajuato (CONCyTEG) and the National Council of Science and Technology (CONACyT). Subsequently, in 2009, the INIFAP Biofertilizer Team, through the “Tecnologías de Producción y Uso de Biofertilizantes” project funded by SAGARPA (Agreement No. 143060011), developed native collections of monosporic mycorrhiza cultures to improve the bioproducts manufactured by INIFAP. In 2010, the “Impulso a nuevos productos y procesos de la bioeconomía y de investigación, transferencia de tecnología y uso de biocombustibles, biofertilizantes y abonos orgánicos” project (SAGARPA Agreement No. S19584A410111) helped to improve some of the production processes of the mycorrhizal and bacterial biofertilizers of INIFAP. In addition, this project supported the creation of the first national collection of microbial biofertilizers in Mexico. Several INIFAP researchers located in different agro-ecological zones of Mexico took part in the creation of this collection. They sent plant and soil samples to the Bacterial Biofertilizers Lab located in Celaya, Guanajuato. In this laboratory, microorganisms were isolated using selective media and their growth promotion capabilities evaluated at the laboratory and greenhouse levels. By the end of the project, approximately 5,000 growth-promoting microorganisms from different agroecological zones were part of this collection. These microorganisms were preserved using different microbiological techniques, including slant culture and cryopreservation.

The main objective of this research initiative was to provide Mexican producers with growth-promoting microorganisms isolated from different agro-ecological zones, which could adapt better to the environmental conditions of a particular local area and, in consequence, promote better the growth of the crops. Within this same project, and at the request of SAGARPA, it was proposed to monitor the quality of the main biological products marketed in Mexico, assist in the development of a proposal for an Official Mexican Standard to verify the production and quality control of biofertilizers, and perform validations of biological materials on all the agroecological regions of México using biological products from INIFAP itself, the Asociación Mexicana de Productores, Formuladores y Distribuidores de Insumos Orgánicos, Biológicos y Ecológicos (AMPFYDIOBE; currently AMPBIO), and the Benemérita Universidad Autónoma de Puebla (BUAP).

As part of the objectives of this project, the book *Introducción al Uso y Manejo de los Biofertilizantes en la Agricultura* was published in 2012. This book has been widely cited in Mexico and abroad (Aguado-Santacruz *et al.*, 2012). In 2011, the National Biofertilizer Team of the INIFAP was part of the Proyecto de Investigación en Biofertilizantes y Abonos Orgánicos (SAGARPA Agreement No. S2341HA4310111), which analyzed different basic molecular aspects of the interaction between growth-promoting microorganisms and plants. Likewise, the researchers explored the potential to:

- a) Increase biomass and sugar content in sweet sorghum through the inoculation of microorganisms.

- b) Evaluate different mycorrhizal strains for the control of nematodes in ‘Maradol’ papaya.
- c) Study the effect of inoculation with growth-promoting microorganisms in potato and husk tomato.
- d) Analyze the effect of biofertilizer inoculation on nutrient assimilation in plants.
- e) Analyze the interaction between agro-industrial by-products and mycorrhiza in vegetable cultivation.

CONCLUSIONS

INIFAP has been an essential part of the governmental strategy to improve agricultural profitability, to enhance the quality of agricultural products, and to reduce environmental impacts by minimizing the use of agrochemicals in the field (particularly synthetic fertilizers). In 1999, the success of the first national bioproduct validation by INIFAP set a major precedent for their use in Mexico, leading to the creation of the first interdisciplinary team of INIFAP focused on research, technology transfer, and development of bioproducts (particularly biofertilizers). Since then, INIFAP has played a leading role in the implementation of technologies that lead to the establishment of a more profitable and healthier agriculture with a lower environmental impact. The various INIFAP publications about the use of bioinputs in agriculture —particularly the first handbook about the use and management of biofertilizers— and the intensive technology extension work conducted by the INIFAP scientists throughout the nearly 25 years of the biofertilizer research and training program of the INIFAP have been fundamental for the adoption of this technology in Mexico. Likewise, the monitoring carried out by this interdisciplinary group on the quality of biological products distributed in Mexico has highlighted the urgent need to develop updated regulations on the use of bioinputs in our country that ensure farmers acquire quality products and, thus, exploit the great potential of bioinputs in Mexican agriculture.

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