Essay

# Considerations on the use of biofertilizers as a sustainable agro-biotechnological alternative to food security in Mexico

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## Abstract

Since the Postclassic, Mexica farmers unknowingly took advantage of the great microbial diversity present in the lake bed that they used as a substrate in their agricultural production schemes. Over the years, Mexican agriculture successfully evolved to intensify the countryside and managed to significantly increase agricultural productivity. However, the increased use of synthetic fertilizers as a solution to soil fertility problems led to high economic, environmental and social costs. This essay shows a critical reflection on the current situation in the use of biofertilizers in the Mexican countryside and future considerations to guarantee their successful use, and thus contribute to national food security in a sustainable way.

**Keywords:** plant growth promoting bacteria, soil, sustainability.

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## The development of agriculture in Mexico and worldwide

Records of agricultural activity in Mexico date back to the Postclassic, where the Mexicas - inhabitants of the Xochimilco and Chalco lake area (1200 to 1350 AD) - designed a rudimentary hydroponic system called 'Chinampas', in which the muddy lake bed (with abundant microbial diversity) to establish crops. During this period, the objective of agriculture was to supply food to the growing pre-Hispanic cities (Bastida-Tapia, 2017).

With the arrival of the Europeans, in colonial Mexico (from 1520), metal farming tools, draft animals (cattle and oxen) and transport (horses, donkeys and mules) were incorporated into agriculture and the monoculture incorporating crops such as wheat, sugar cane, tobacco, cotton and coffee. The colonial system was sustained; starting with the exploitation of indigenous peoples and ecosystems, breaking the agroecological balance that pre-hispanic peoples maintained and beginning with the depletion of Mexican soils (WRM, 2004; Cruz-León *et al*., 2010).

Subsequently, Mexican agriculture can be broadly described in three stages: i) growth stage (1940-1957), where agriculture was promoted as the main economic activity, managing to represent up to 19% of the national gross domestic product (GDP); ii) development stage for the country (1958-1981), where the agricultural sector was a key component in supplying the industrialization of Mexico; and iii) current stage (from 1982 to date), in which agriculture is affected by the 1982 crisis, external debt and the fall in the exchange rate, but at the same time it was favored by the opening of the economy of the Free Trade Agreement (NAFTA) that diversified products and increased the use of agricultural technology (Gómez-Oliver, 1995).

On the other hand, the accelerated growth of the population worldwide in the middle of the last century demanded the continuous increase in the production and quality of agri-food products (Huerta *et al*., 2018). The aforementioned prompted the Phytopathologist Norman E. Borlaug, considered 'the father of modern agriculture', to undertake an innovative project in 1944 that consisted of increasing agricultural productivity by incorporating technological advances to enhance crop yields, to which it was called the Green Revolution (Cerutti, 2019).

The Green Revolution focused on the monoculture of improved varieties; for example, among the agronomic traits for the cultivation of wheat, the following stood out: i) the considerable shortening of the stems, an important characteristic that favors their yield and prevents plant stagnation due to the increased weight of the grains; and ii) increased adaptability to latitude, elevation, and other environmental factors. This increased the wheat yield from 2 t $ha^{-1}$ to 8 t $ha^{-1}$ (Dieguez *et al*., 2010).

Furthermore, the agricultural practices used for these improved varieties were based on the use of irrigation, mechanization, and the application of synthetic pesticides and fertilizers, and the application of nitrogen fertilizer (N) worldwide increased from 32 Tg N (million metric tons) in 1970 to approximately 80 Tg in 1990 (McCullough and Matson, 2016).

In this way, the Green Revolution was a success in boosting the production of the main cereals worldwide (wheat, rice and corn, among others); however, its large-scale impact has been disputed. The application of high doses of synthetic fertilizers from the 60's (up to 250 kg $ha^{-1}$ today) (McCullough and Matson, 2016) caused that between 1960 and 2000, agricultural yields increased 208% for wheat, 109 % for rice, 157% for corn, 78% for potatoes and 36% for cassava in developing countries, generating great economic and food income worldwide (Lobell *et al*., 2005).

However, in several developing countries including Mexico, high-yielding varieties and intensive planting techniques were acquired almost entirely by large commercially established farmers, unlike small rural farmers who did not have the same opportunities (Harwood, 2009), promoting economic polarization, as well as the devaluation of traditional techniques and the rural environment (de Grammont, 2010), in addition, the excessive use of synthetic fertilizers generated a negative impact at the environmental level, putting the health of producers, consumers and productive resources, genetics and biodiversity (Naylor *et al*., 2001).

**Use of synthetic fertilizers and their impact on agricultural activity in Mexico**

The application of synthetic fertilizers in agriculture greatly increases the yield of various crops, which is why their use increased 27.1% in Latin America and the Caribbean during the 2006-2017 period (Reyes and Cortés, 2017). Despite these benefits, various authors report that excessive and inappropriate use of synthetic fertilizers causes serious environmental and ecological problems (Snyder, 2009).

The potential for contamination of a synthetic fertilizer is closely related to its efficient use by the crop, which varies depending on factors such as the type of fertilizer and its presentation, the time and manner of supplying it to the crop and the industrial technology of manufacturing (García, 2009). In this way, the inappropriate use of synthetic fertilizers directly impacts agricultural activity, generating high economic costs, environmental deterioration and social segregation.

Economic impact. Taking corn cultivation as an example, producing one hectare under a conventional agricultural scheme in the autumn-winter 2011 to spring-summer 2012 period cost between $9 763.00 and $24 033.00 mexican pesos, allocating between 23.3% and 25.9% for fertilization and pest and weed control; However, during the period 2019 to 2020 the cost increased from $15 112.00 to $42 007.00 mexican pesos, allocating from 31% to 35% of this cost to fertilization and phytosanitary control (FIRA, 2020). Even when the cost range is wide [due to the production system (irrigation or storm), the agroclimatic variables, the expected yield, the degree of technification, among others], the increase in the percentage of this destined to the fertilization and phytosanitary control with products of synthetic origin.

Likewise, this cost is impacted by the increase in the prices of these synthetic inputs, the fluctuation of the prices of the product in the market and, where appropriate, by the variation in the financial services that the producer uses. This model is repeated in the various crops produced in Mexico and directly affects the producer's profit margin and the consumer's purchasing level.

Environmental impact. This is caused by the degree of disturbance that agricultural practices cause to the environment, mainly on the quality of the soil, water, air, and biodiversity, as well as on the health of people, animals and plants of a given region (Balmford *et al*., 2018). Current production models base crop management on the excessive use of synthetic fertilizers for crop nutrition and toxic compounds for pest, disease and weed control (FAO, 2002). The high concentration of these compounds in soil, water and air, generates an imbalance in the biogeochemical cycles and the trophic chains of the agricultural areas, having as an effect the decrease of the productive capacity, the difficulty in controlling pests, diseases and weeds that have generated resistance (Mandal *et al*., 2020).

Social impact. The current agricultural model, adopted since 1958, has also had a social sequel, since it has generated an economic-social polarization accompanied by segregation and discrimination towards the rural sector (de Grammont, 2010). Large producers and transnational companies invest in highly technical agriculture, which has high economic-environmental costs, and small producers, unable to compete in these conditions, rent their land or end up working it as agricultural employees, receiving low wages that barely cover their feeding needs (López-Feldman and Herández-Cortés, 2016).

During the last decades, the success of conventional agricultural systems has been important and significant; however, these have caused the loss of biological diversity, reduction of forest resources, soil erosion, climatic changes, among others. In this context, the current challenges of national agricultural production focus on: i) generating changes in agrarian policies that promote the disaggregation of the social and economic polarization of the countryside (which has prevailed in Mexican agriculture), promoting the rural sector and conserving it as an instrument to promote food security in the country; and ii) to migrate gradually and progressively towards cost-effective agricultural production methods and with a holistic vision that allows the recovery and preservation of soils, water, genetic resources and that do not pose a risk to environmental, producer or consumer health.

**Microbiology and its relationship with agriculture: the case of biofertilizers**

Plants are in constant interaction with their environment and are mainly related to the soil, which is a large and complex ecosystem in which large microbial populations also inhabit. Soils with higher organic matter contents (>2%) contain an increased population and diversity of microorganisms, mainly made up of bacteria, actinomycetes, fungi and algae (Jacoby *et al*., 2017), whose activity is strongly related to fertility and stability of the edaphic resource (de los Santos-Villalobos *et al*., 2018).

In this way, the soil can host a population of 108 to 109 bacterial cells per gram; however, if it is subjected to any type of stress (lack of water and nutrients, soil salinity, heavy metal contamination, among others) as a consequence of agricultural practices, the population can decrease up to 104 bacterial cells per gram of soil (Valenzuela-Aragón *et al*., 2019). Thus, microbial diversity in soils is estimated at more than 105 species, which are involved in i) nutrient cycling; ii) decomposition of organic matter; iii) photosynthesis; iv) bioremediation; and v) the control of plant diseases, among others (de los Santos-Villalobos *et al*., 2018).

The rhizosphere, a portion of soil on which the roots of plants have influence through their exudates, has the highest population and diversity of microorganisms, which compete for space and nutrients (Jacoby *et al*., 2017). These microbial interactions directly impact soil-plant-microorganism-environment relationships and have a positive or negative impact on the growth and development of agricultural crops (Cano, 2011).

Among the microorganisms that inhabit the rhizosphere, those with the ability to promote crop development and yield are distinguished; through direct and indirect mechanisms (Figure 1), which are called plant growth promoting microorganisms (MPCV). The direct mechanisms improve the nutritional status of the plant by increasing the volume of exploration and functionality of the roots, the uptake of water, the availability and absorption of nutrients and the physiology of the entire plant (Kumar *et al*., 2015). This is carried out through the production of growth regulators, organic acids, enzymes, metalophores, vitamins and other secondary metabolites that directly impact plant growth (Grageda-Cabrera *et al*., 2012; Moreno-Reséndez *et al*., 2018).

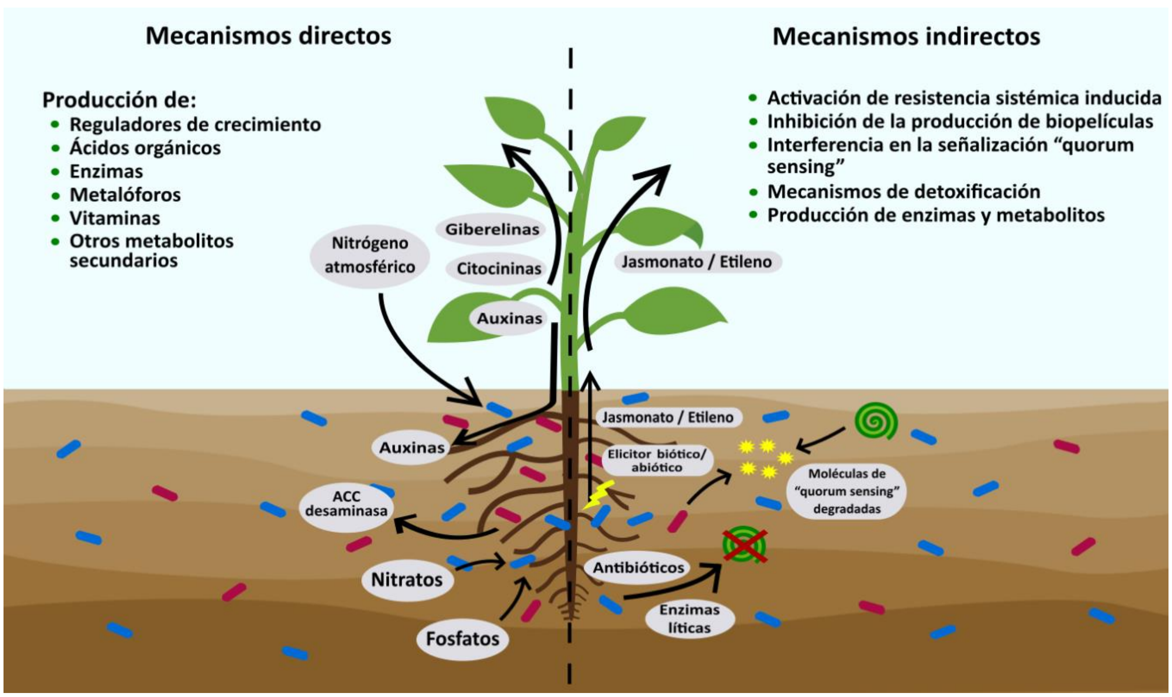


**Figure 1. Direct and indirect mechanisms present in plant growth promoting microorganisms (MPCV).**

On the other hand, indirect mechanisms are involved in the protection against stress caused by abiotic and biotic factors, among which the induction of resistance to adverse environmental conditions and to phytopathogens stands out. The latter involves activation of induced systemic resistance, inhibition of biofilm production, interference in 'quorum sensing' signaling, activation of detoxification mechanisms of virulence factors, and the production of enzymes/metabolites involved in specialized functions (Moreno-Reséndez *et al*., 2018; Villarreal-Delgado *et al*., 2018).

The former has promoted the use of MPCV as active ingredients in biofertilizers, which are bio-formulated that contain live microorganisms that, when applied in foliar, irrigation or soil, promote the development of plants; through the direct and indirect mechanisms previously mentioned (Santoyo *et al*., 2019). Among the bacterial genera most used in the production of biofertilizers, *Rhizobium*, *Bacillus* and *Pseudomonas* stand out.

*Rhizobium* species, in addition to fixing atmospheric nitrogen, increase growth, yield and number of nodules per root and mobilize phosphorus (Saharan and Nehra, 2011). Recent research in this bacterial genus as a promoter of plant growth focuses on analyzing its effect on i) the structure of root-associated microbial communities (Jha *et al*., 2020); ii) develop biofertlizers for multiple leguminous crops (Passricha *et al*., 2020); iii) introducing *Rhizobium* cells into seeds using vacuum technology to avoid loss of the inoculum (Lekatompessy *et al*., 2020); and iv) evaluate the effect of co-inoculation of *Rhizobium* and endomycorrhizal spores (Kiuk *et al*., 2019).

*Bacillus* is the most abundant genus in the rhizosphere, strains of *B. subtilis*, *B. megaterium*, *B. mucilaginosus*, *B. pumilus* and *B. licheniformis* are the most studied species for their colonization capacity, solubilization of potassium and phosphorus, increased development, length and dry matter of the root, and yield of the plants (Bhattacharyya and Jha, 2012; de los Santos-Villalobos *et al*., 2019; Villa-Rodríguez *et al*., 2019). Currently, studies on this bacterial genus focus on i) new strategies for the production of its spores in solid or liquid culture (Hindersah *et al*., 2020); ii) evaluate the effect of *Bacillus* strains on the content of phenolic compounds in plants (Jiménez-Gómez *et al*, 2020); iii) determine the harvest time to maximize the nutritional content of biofertilized fruits with *Bacillus* strains (Cisternas-Jamet *et al*., 2020); and iv) analyze the level of expression of the genomic potential of *Bacillus* strains during the plant-rhizosphere interaction (Borriss, 2020).

The *Pseudomonas* genus is ubiquitous in the soil, the most effective strains of this genus being those belonging to the *Pseudomonas fluorescentes* species, which help in maintaining the health of the soil; through, a great metabolic and functional diversity (Lugtenberg and Dekkers, 1999). Currently, research on the generation of biofertilizers containing strains of this bacterial genus is focused on i) analyzing the potential of genetically modified Pseudomonas strains on the yield of agricultural crops (Wang *et al*., 2020); ii) identify plant growth promoting strains with the ability to bioremediate soils contaminated with heavy metals (Khashei *et al*., 2020); iii) identify strains with the ability to increase tolerance to salinity in agricultural crops (Lami *et al*., 2020); and iv) evaluate the participation of specific genes of some strains in the promotion of plant growth (Tahir *et al*., 2020).

On the other hand, among the fungi that promote plant growth, the most studied strains belong to the *Glomus* genus, which have been reported as mitigating agents of the effects induced by water stress in plants (Mota *et al*., 2020) and increase plant growth by synergistic action when co-inoculated with bacteria promoting plant growth (Nadeem *et al*., 2014). Furthermore, various strains of *Trichoderma* have been studied for their i) potential for antagonism and mycoparasitism against plant pathogens; ii) ability to improve plant growth under abiotic stress conditions (Hermosa *et al*., 2012); iii) ability to increase pigment content in plants (Metwally and Al - Amri, 2020); and iv) ability to enhance the microbiota and enzymatic activity of the soil (Zhang *et al*., 2020).

## Considerations in agricultural management and factors that limit the efficiency of biofertilizers

Currently, biofertilizers are successfully used in many developed countries, while their use and approval by the agricultural sector in developing countries is limited by various factors, ie. knowledge about its proper management (Grageda-Cabrera *et al*., 2012). In this way, it is important to know and disseminate scientific information on the correct use of biofertilizers, their associations with plants, and the agrosystem and management conditions that affect these interactions.

The recommended methods for applying biofertilizers are seed inoculation, seedling inoculation by immersion, application in the irrigation system and application to the soil. Furthermore, the main recommendations for the successful use of biofertilizers are mentioned below (Figure 2).

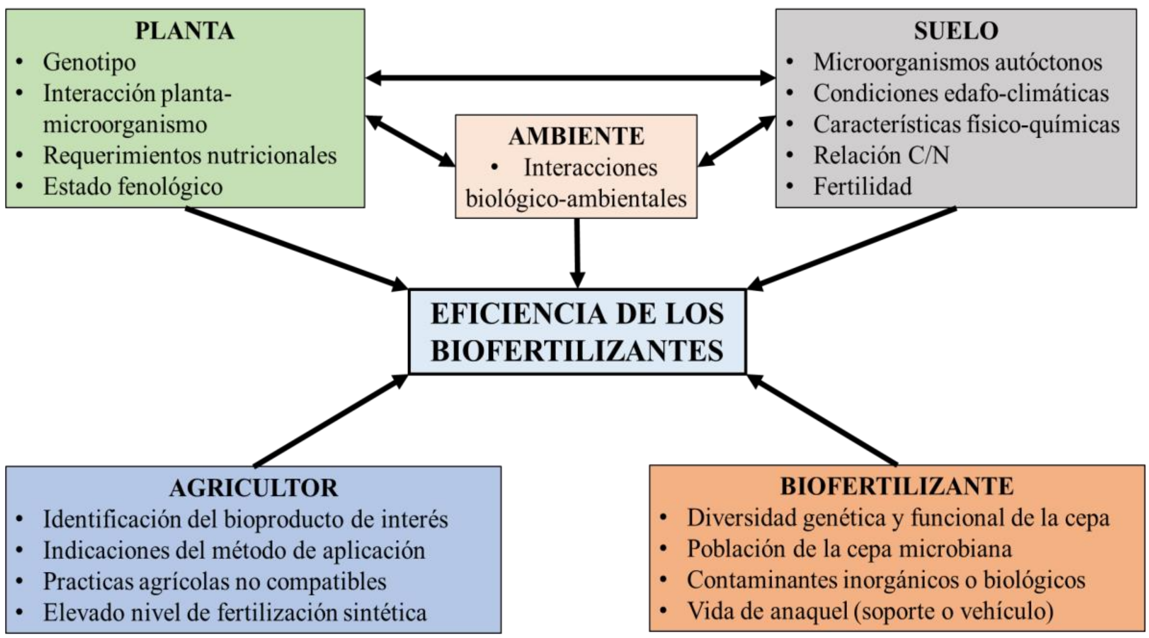


**Figure 2. Considerations for the successful use of biofertilizers in the agricultural sector.**

A) the biofertilizer must contain an appropriate live population of the strain reported as an active ingredient and be free of contaminating microorganisms (Sanjuan-Pinilla and Moreno-Sarmiento, 2010). B) the biofertilizer must be selected based on the active ingredient (microbial strain), the crop of interest, the edapho-climatic conditions and agricultural practices used; Furthermore, said bioproduct must be used before the expiration date (Moreno-Reséndez *et al*., 2018); C) the field application of biofertilizers must be done according to what is established by the supplier. For example, the use of adherent compounds is decisive for the treatment of seeds with biofertilizers (Bojorques *et al*., 2010); and D) biofertilizers should be stored in a cool, dry place, away from direct sunlight and heat, and used in correct combinations with agrochemicals (Sanjuan-Pinilla and Moreno-Sarmiento, 2010).

The success of the application of biofertilizers also depends on the support or carrier, which determines the shelf life of the product and the persistence of its microorganisms during the phenology of the crop or at the stage of interest for its beneficial effect (Ansari *et al*., 2015). Thus, the population of viable inoculated cells is of great importance for the promotion of the expected growth in the culture, since an excessive or limited number of these can hinder the germination of the seed or the growth of the plant, respectively (Boddey and Dobereiner, 1995).

On the other hand, knowledge of the nutritional and environmental requirements of the microorganisms contained in the biofertilizers is decisive for their effectiveness, as well as their capacity for plant colonization, adaptation to the soil and interaction with native microorganisms (Khalid *et al.*, 2004; Grageda-Cabrera *et al*., 2012). Nutrient availability, pH and salinity determine the survival of microorganisms in the soil, the shortage or excess of any chemical compound can rapidly decrease the inoculated microbial population.

The content of organic matter and nitrogen (C:N ratio) in the soil significantly affect the functions of promoting plant growth of the strains contained in biofertilizers (Dobbelaere *et al*., 2001; Grageda-Cabrera *et al*., 2012). Furthermore, it has been reported that the lower the soil fertility, the greater the stimulation of plant growth by biofertilizers, since they mobilize the unavailable and recalcitrant elements (De Freitas and Germida, 1990) and other studies show that the high level synthetic fertilization to the crop inhibits or decreases the effectiveness of these bioproducts. Thus, there are currently numerous studies focused on knowing the economic, environmental and functional balance for the use of biofertilizers in combination with reduced levels of synthetic fertilization in agricultural crops (Spolaor *et al*., 2016). Thus, the use of biofertilizers will positively impact current and future food security, and the mitigation of the negative economic, social and environmental effects generated by conventional agricultural production systems.

**Success stories in the use of biofertilizers in Mexico**

Biofertilizers have been widely accepted internationally, as they have demonstrated various advantages in the field. In Mexico, various investigations have been carried out on the development, innovation and validation of biofertilizers. For example, a biofertilizer that has shown positive and significant impacts is the one developed by Trujillo-Roldan *et al*. (2013). The authors achieved an increase of 70% in the weight of the above-ground biomass in corn and 95% in the increase in biomass in the ears by the application of *Azospirillum brasilense*, compared to a synthetic fertilizer. Parra-Cota *et al*. (2014) reported that through the inoculation of two *Burkholderia* species (*B. ambifaria* Mex5 and *B. caribensis* XV) the yield was increased to 155.4% and 41.4% in amaranth (compared to the non-inoculated treatment), respectively, under conditions of sandy soils. Similarly, Rojas-Padilla *et al*. (2020) reported that inoculation of wheat by a bacterial consortium comprised of *B*. *megaterium* TRQ8 + *B*. *paralicheniformis* TRQ65 showed the greatest significant increases (*vs* non-inoculated treatment) in air and radical length of 6 and 10%, respectively, while the aerial and radical dry biomass increased 60% and 82%, respectively.

Likewise, mycorrhizal fungi have been shown to be highly efficient in establishing associations with plants. For example, Aguirre-Medina *et al*. (2004) reported that the co-inoculation of some mycorrhizal fungi (*Rhizophagus intraradices*) and strains of *Rhizobium* and *Azospirillum* promoted plant development of annual and perennial crops. Recently, the inoculation of mycorrhizal fungi to the wheat crop led to an increase in grain production of up to 1 291 kg $ha^{-1}$ (Grageda-Cabrera *et al*., 2011).

On the other hand, Hipolito-Romero *et al*. (2017) reported that the co-inoculation of two nitrogen-fixing strains (*Azospirillum brasilense* UAP-151 and UAP-154) and two phosphorus-solubilizing strains (*Chromobacterium violaceum* BUAP 35 and *Acinetobacter calcoaceticus* BUAP40) showed beneficial effects on agronomic parameters of the plants, increasing the height (49%), the diameter (127%), the number of branches (300%) and the number of leaves (500%), compared to plants treated with synthetic fertilizers.

Although only some success stories in the use of biofertilizers in Mexico are presented here, the acceptance and application of this agro-biotechnology will undoubtedly increase, due to its effectiveness, low cost, zero negative impacts on the environment, and being a goal of national biofertilizer program to promote sustainable agriculture. Thus, knowledge of the benefits of the use of biofertilizers will undoubtedly allow decisions to be made focused on the production of food in a sustainable way in Mexico.

## Conclusions

Currently, the development of biofertilizers must consider various aspects, among which are: i) the selection and evaluation of effective native strains to obtain optimal and sustainable yields, enhance plant-microorganism interaction, target crops, response to environmental factors and preservation of native microbial resources; ii) research on improved inoculant formulations, shelf life, residual benefits, persistence, and stress adaptations of microbial strains; iii) monitoring of quality control in the stages of production, distribution, field application through strict compliance with the guidelines and regulations; iv) the integration of biofertilizers to other agroecological practices adapted to different farming systems to achieve sustainable agriculture; v) the development of policies and strategies that allow biofertilizers to reach farmer groups, research and learning institutions, private and public organizations; and vi) establish networks that involve local institutions, the private sector and research organizations to develop effective models for the production of biofertilizers with microorganisms native to the regions where they will be applied. This will lead to the efficient use of biofertilizers as a sustainable strategy to achieve current and future food security in Mexico.

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