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USE OF MICROBIAL CONSORTIA IN AGRICULTURE AS AN ALTERNATIVE FOR ACHIEVING SUSTAINABLE AGRICULTURA

USO DE CONSORCIOS MICROBIANOS EN LA AGRICULTURA COMO ALTERNATIVA PARA LOGRAR UNA AGRICULTURA SOSTENIBLE

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Use of microbial consortia in agriculture as an alternative for achieving sustainable agriculture

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ABSTRACT

Agriculture is established as a fundamental activity that sustains the basis of our food supply. Through techniques that respect and preserve the environment, it is possible to achieve efficient agricultural production that meets the growing needs of our population, thus bringing us closer to the longed-for food sovereignty and meeting the sustainable development goal of zero hunger proposed by the United Nations (UN). In this review, several research studies that explore the implementation of new fertilization techniques are presented. These techniques use growth-promoting bacteria, which operate through both direct and indirect mechanisms. Studies show how these bacteria can significantly improve the production of grains and vegetables essential for food in Mexico and other countries. Thus, agriculture becomes a key pillar for a more sustainable and food-secure future.

***Keywords*:** agroindustrialization, biofertilizers, growth-promoting bacteria, agricultural productivity, sustainable agriculture

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Uso de consorcios microbianos en la agricultura como alternativa para lograr una agricultura sostenible

RESUMEN

La agricultura se establece como una actividad fundamental que sustenta la base de nuestro abastecimiento alimentario. A través de técnicas que respeten y preserven el medio ambiente, es posible lograr una producción agrícola eficiente que satisfaga las crecientes necesidades de nuestra población, acercándonos así a la anhelada soberanía alimentaria y cumpliendo con el objetivo de desarrollo sostenible de hambre cero propuesto por la Organización de las Naciones Unidas (ONU). En esta revisión se presentan varios estudios de investigación que exploran la aplicación de nuevas técnicas de fertilización. Estas técnicas utilizan bacterias promotoras del crecimiento, que actúan a través de mecanismos directos e indirectos. Los estudios muestran cómo estas bacterias pueden mejorar significativamente la producción de granos y hortalizas esenciales para la alimentación en México y otros países. De este modo, la agricultura se convierte en un pilar fundamental para un futuro más sostenible y con mayor seguridad alimentaria.

Palabras clave: agroindustrialización, biofertilizantes, bacterias promotoras del crecimiento, productividad agrícola, agricultura sustentable

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INTRODUCTION

Agriculture is of great importance throughout the world, as it is through this activity that we obtain the food that is the basis of our diet. An important aspect is soil fertility since good production depends on it. Soil fertility depends on abiotic and biotic factors, the latter including microorganisms such as bacteria. In the soil, a great diversity of microorganisms of different species work together to form a consortium. A microbial consortium is a natural association of two or more microbial populations of various species that act together as a community in a complex system where all benefit from each other's activities (Ochoa-Carreno *et al*., 2010). Microbial consortia are multiple microbial populations that interact and perform complex functions that individual populations cannot, and microbial consortia can be more robust to environmental fluctuations (Brenner *et al*., 2008). In the rhizosphere we can find different microorganisms such as bacteria that can help in the growth of plants; these are called Plant Growth Promoting Rhizobacteria (PGPR), which have been studied individually and in the consortium as growth stimulators in different plants that produce the staple foods of consumption in the diet of mexicans. The relevance of this topic lies in the fact that by achieving favorable results in the growth and production of food, such as grains and vegetables, we can satisfy our food needs and, in turn, strengthen food sovereignty. To this end, adopting sustainable strategies that respect the environment is essential.

This research aims to analyze the effect of bacterial consortia in the Mexican agrofield. To achieve the goal of food sovereignty, it is essential that these microbial consortia are easily accessible to agricultural producers, and their local production is ideal.

METHODS

The words or phrases searched were "agroindustrialization 5.0," "biofertilizers," "efficient microorganisms," "agriculture," "food sovereignty," "rhizobacteria," "bacterial consortium," and "plant growth promoting bacteria." Scientific literature was searched using Scholar Google, Scopus, Web of Science, Science Direct, and PubMed. For the review, 39 references were selected from the 85 resulting from the search; these included reports, research articles, and review articles published between 2010 and 2023.

DISCUSSION

Sustainable agriculture, agriculture, and technification 5.0 in Mexico

The Food and Agriculture Organization of the United Nations (FAO) defines food sovereignty as the right of communities to develop sustainable strategies for food production, distribution, and consumption, ensuring access for all. This concept underlines the importance of small- and medium-scale agriculture and respecting local cultures and diverse agricultural practices, especially among peasants, fisherfolk, and indigenous communities, where women play a key role. Food sovereignty is aligned with sustainable agriculture, promoting methods that protect the environment while producing essential foods and ensuring that agricultural practices are ecologically and socially responsible. Family farming fosters connections between producers and consumers, enhancing market equity and supporting food sovereignty (FAO, 2011; Ramirez-Juarez, 2023). In Mexico, agriculture is vital for providing staple foods such as grains and vegetables. Small- and medium-scale producers primarily cultivate essential crops like corn, beans, and rice to ensure food security. According to the 2022 Census of Agriculture and Livestock by INEGI, corn is the most widely grown crop, followed by beans and vegetables like pumpkin, potatoes, and tomatoes. These crops are integral to the Mexican diet and significantly contribute to local economies

The Secretariat of Agriculture and Rural Development (SADER, Spanish acronym) recognizes tomatoes as a critical vegetable in Mexico and globally due to their economic significance and nutritional benefits. However, most crops are cultivated using conventional methods that heavily rely on chemical fertilizers (SADER, 2022). While these practices can lead to initial high yields, their indiscriminate use often results in soil degradation, fertility loss, and water contamination, adversely affecting ecosystems and human health. Research indicates that enhancing bean production could improve food sovereignty; a study in northern Mexico highlighted that domestic bean production is insufficient to meet demand, necessitating imports. With only 1.2 % of land having high production potential available for beans, there is an opportunity to meet domestic needs while generating surpluses for other regions (Moctezuma-Lopez, 2022).

The implementation of Agriculture 5.0 is addressing food needs sustainably by utilizing technologies such as robotics and artificial intelligence to enhance productivity. The Federal Telecommunications

Institute (IFT, Spanish acronym) observes that traditional agriculture coexists with advanced methods in various regions. Digital agriculture relies on devices that process extensive data on climate, crops, soils, and more (Ponce-Gonzalez, 2023). The Secretariat of Agriculture offers tools like the "Atlas SIAP" app for agricultural product information, though data on user adoption of these technologies is limited (Chavez-Gonzalez et al., 2022). The Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP) has successfully implemented irrigation technologies that conserve water while maintaining yields during droughts (INIFAP, 2023). These advancements highlight the potential for integrating technology into sustainable agricultural practices in Mexico.

Plant growth promoting rhizobacteria

Mexican biotechnology has become an essential tool in agriculture, primarily through plant growth-promoting rhizobacteria. These beneficial bacteria colonize plant roots, improving their development by facilitating nutrient and water absorption and promoting disease resistance. Institutions such as the National Autonomous University of Mexico (UNAM) are researching these rhizobacteria to optimize their application in local crops such as corn and chili (Velasco-Jiménez *et al*., 2020).

The National Laboratory for Plants under Controlled Conditions (PlanTECC) specializes in using beneficial microorganisms, analyzing their effectiveness in increasing agricultural productivity, and promoting sustainable practices that respect the environment. This research helps reduce dependence on chemical fertilizers and pesticides, contributing to more sustainable agricultural systems (Cruz-Cardenas *et al*., 2021).

The rhizosphere hosts a rich diversity of microorganisms, mainly bacteria, which play essential roles in soil health and offer numerous plant benefits. Among these, PGPR are a diverse group found in the rhizosphere and on root surfaces, enhancing plant growth quality and extent (Ahmad *et al*., 2008). PGPRs benefit plants through direct mechanisms like biofertilization, root stimulation, rhizoremediation, and stress management. Indirectly, they provide biological control by promoting growth and mitigating disease impacts through antibiotics, systemic resistance induction, and nutrient competition (Egamberdieva et al., 2014). These beneficial rhizobacteria enhance water and nutrient uptake while improving stress tolerance (Backer *et al*., 2018).

The use of plant growth-promoting rhizobacteria also supports food sovereignty objectives, enabling local farmers to improve their yields and resilience to environmental challenges, which is critical for the future of agriculture in Mexico.

Bacteria in crop development

Bacteria play a vital role in agriculture by enhancing crop production through various direct and indirect mechanisms. A study conducted in the Yaqui Valley, northwestern Mexico, focused on characterizing native bacteria from maize rhizospheres for their potential as plant growth promoters. Researchers identified strains such as *Bacillus sp*., *Advenella incenata*, *Pantoea dispersa*, and *Rhizobium*, which demonstrated capabilities to synthesize indoles, produce siderophores, and solubilize phosphates. Inoculating maize with these strains led to significant increases in plant height, shoot and root dry weight, and critical chlorophyll index value, indicating that native bacteria from the Yaqui Valley can effectively promote sustainable maize growth (Amezquita-Aviles *et al*., 2022). Gutierrez-Calvo *et al*. (2022) further explored the effects of two *Bacillus subtilis* strains (GBO3 and IN937b) on maize growth. They tested 10^7 and 10^8 UFC.mL^{-1} concentrations, finding that GBO3 at 10^8 UFC.mL^{-1} and IN937b at 10^7 UFC.mL^{-1} significantly enhanced maize growth.

Ali *et al*. (2022a) also studied the *Bacillus mycoides* strain PM35, which exhibited resistance to NaCl stress up to 3 M and demonstrated plant growth-promoting traits. Inoculating maize with *Bacillus mycoides* (PM35) alleviated salt stress and improved both shoot and root lengths, highlighting its potential to support plant growth under saline conditions. In another study, Ali *et al*. (2022b) examined the effects of *Enterobacter cloacae* PM23 under salinity stress. Their biochemical and molecular characterization revealed that this strain positively influenced maize growth by enhancing biomass, photosynthesis, and overall plant health while alleviating salt stress. This environmentally friendly approach offers a strategy for improving crop performance amid salinity challenges. Research on PGPR has also targeted bean crops.

In the Mexican agricultural context, PGPR can be fundamental to facing challenges such as drought and salinity. Research such as that of Karmakar et al. (2021) has shown that microorganisms such as *Mycobacterium sp*. and *Bacillus sp*. improve the growth of rice crops under water stress by solubilizing phosphates and fixing nitrogen. Likewise, using strains such as *Pseudomonas mendocina* and *Azotobacter vinelandii* in wheat crops has shown significant nutrient transfer and salt tolerance benefits. These strategies can boost sustainability and productivity in the Mexican countryside.

While indigenous microorganisms offer significant advantages due to their local adaptation and functional diversity, *Bacillus subtilis* strains provide a more standardized and proven solution to improve plant growth and control diseases in diverse agricultural contexts. Both approaches are complementary and highlight the importance of microorganisms in sustainable farming practices.

Use of plant growth promoting bacterial consortia in agriculture

Research on bacterial consortia applied to agricultural fields has gained traction across various countries, particularly concerning the cultivation of cereals and vegetables. Studies have focused on utilizing PGPR in maize, employing consortia composed of six bacterial strains from the genera *Bacillus*, *Streptomyces*, and *Pseudomonas*. These consortia were tested *in vitro* and later applied to maize plants, resulting in enhanced growth parameters compared to single inoculant treatments. This suggests that such consortia can effectively address low yields and provide a reliable alternative to chemical fertilizers (Olanrewaju *et al*., 2019).

The application of PGPR has shown promising results across various soil types. One significant study examined a consortium of rhizobacterial strains, including *Bacillus cereus*, *Bacillus altitudini*, *Delftia*, and *Stenotrophomonas maltophilia*, aimed at improving maize production in oily sludge conditions. The findings indicated that this consortium effectively reduced oxidative stress in plants and improved maize tolerance, thereby enhancing nutrient uptake. This consortium could also be utilized for remediating soils contaminated with oily sludge from oil refineries (Shahzad *et al*., 2020).

In bean cultivation, PGPR has demonstrated beneficial effects. A study by Calero-Hurtado *et al*. (2022) assessed the impact of biostimulants ME-50® and FitoMas-E® on bean plants during the late planting season using a 2x2 factorial design. Results showed that the combined application of these biostimulants significantly increased growth and productivity compared to individual applications, yielding increases of 10 % and 71%, respectively. Similarly, Calero-Hurtado *et al*. (2023) explored the co-application of ME-50® and BIOBRAS-16® on common beans during mid and late planting seasons. Their findings revealed significant improvements in trifoliate leaf count, plant height, dry mass of aerial parts, pod count per plant, and overall yield.

Rice production is critical for food security, prompting research into enhancing its yields.

Bandyopadhyay *et al*. (2022) identified a synergistic interaction between rice (*Oryza sativa*), *Piriformospora indica*, and *Azotobacter chroococcum*. Co-inoculating plant roots with both fungi and rhizobacteria resulted in better growth and nutrient uptake than using either microbe alone. Additionally, Rios-Ruiz *et al*. (2020) conducted experiments in Peru that demonstrated how selected native bacterial consortia could reduce nitrogen fertilizer use by up to 25 %. In potato cultivation, research has focused on combating stem rot through the application of growth-promoting bacteria alongside synthetic fertilizers. Strains like *Azotobacter chroococcum*, *Azospirillum lipoferum*, and *Pseudomonas putida* effectively controlled *Neocosmospora rubicola* infestations (Riaz *et al*., 2022). Another study combined *Bacillus subtilis* with *Trichoderma harzianum* to suppress common scab caused by *Streptomyces spp*., resulting in increased tuber yields over two years (Wang *et al*., 2019).

Research involving crops from the *Solanaceae* family has also been conducted to combat pathogens such as *Fusarium oxysporum f. sp. radicis-lycopersici* and *Rhizoctonia solani* in potatoes and tomatoes. Four PGPR strains *Azospirillum brasilense*, *Gluconacetobacter diazotrophicus*, *Herbaspirillum seropedicae*, and *Burkholderia ambifaria* were tested for their efficacy against these infections. The study concluded that this consortium could serve as a promising alternative to chemical agrochemicals for biocontrol (Pellegrini *et al*., 2020).

Moreover, research on tomatoes has investigated the effects of heterotrophic bacteria and cyanobacteria consortia on seedling development. These microbial formulations significantly stimulated growth and aerial development (Toribio *et al*., 2022). Paganin *et al*. (2023) developed a biofertilizer using eight indigenous strains from genera like *Delftia* and *Pseudomonas*, which yielded results comparable to chemical fertilizers across various tomato varieties, highlighting its potential for sustainable agricultural practices through knowledge-based formulations.

Use of bacterial consortia in Mexican agriculture

Bacterial consortia in Mexican agriculture have been evaluated with various staple crops. A study in Villaflores, Chiapas, assessed three microbial consortia—MM1, MM2, and MM3—isolated from the "La Sepultura" Biosphere Reserve alongside a control of compost with ammonium sulfate. Researchers used a Latin square design (4x4) on 1225 m² with Pioneer P4082W maize to measure plant height, stem diameter, leaf area, fresh biomass, and total leaf count. The MM3 consortium significantly enhanced growth and biomass (Macias-Coutino *et al*., 2021). Additionally, a consortium of *Azospirillum brasilense*, *Pseudomonas putida*, *Acinetobacter sp*., and *Sphingomonas sp*. effectively reduced nitrogen fertilizer use while promoting maize growth (Molina-Romero *et al*., 2021).

In a study carried out on bean plants (*Phaseolus vulgaris*), they evaluated the resistance induction response by inoculation of endophytic bacteria against *Rhizotocnia solani* and *Fusarium oxysporum,* using bacterial consortia composed of endophytic bacteria of *Bacillus amyloliquefaciens* strains 53 and 21 using a block design, the results showed that the endophytic bacterial consortia caused an increase in protein concentration and enzyme activity in the bean plant, thus contributing to the resistance mechanism (Castro-del Angel *et al*., 2021).

Research on wheat plants has focused on enhancing seedling biometric characteristics through injection with a native consortium of *Bacillus megatherium*, *Bacillus cabrales*, *Bacillus paralicheniformis*, and *Bacillus subtilis*. After 30 days in controlled conditions, these strains demonstrated the ability to synthesize siderophores, indoles, and solubilize phosphates while also tolerating thermal (43.5 °C), hydric (PEG 10 %), and saline (NaCl 5 %) stress. Inoculated seedlings showed significant improvements in aerial length, root length, stem diameter, dry weight, and biovolume index compared to non-inoculated seedlings, highlighting the consortium's growth-promoting potential (Robles-Montoya *et al*., 2020).

Research on plant growth promoters extends to vegetables like tomatoes, aiming to enhance growth and yield. One study evaluated the effects of zinc oxide nanoparticles (NPsZnO) applied through foliar and drench methods, alongside rhizospheric microorganisms. Using the commercial product Biogea Plantek®, which contains *Glomus intraradices* and *Azospirillum brasilense*, the results indicated that the combination of nanoparticle dosage, application method, and substrate microorganisms created a positive synergistic effect on tomato plant growth and biomass (Vargas-Martinez *et al*., 2023).

PGPR can enhance growth by protecting against pathogens. A study in Saltillo, Coahuila, investigated the antagonistic effects of three microbial consortia on three strains of *Fusarium oxysporum f. sp. lycopersici* (FOL) and their impact on wilted tomato (*Solanum lycopersicum*) seedlings in a greenhouse. The evaluated consortia—Soil Pro (SP), SOS®, and SSB®—comprise bacteria, yeasts, and mycorrhizae. Results showed that SP increased tomato seedling growth by 21 %, while SP and

SOS® reduced seedling damage severity by 37 % (Limon-Corona *et al*., 2022).

Significantly, these bacteria improve nutrient availability and water uptake, contributing to plant resistance to disease and adverse conditions. These practices benefit the environment and human health by reducing dependence on chemical fertilizers and pesticides, promoting a more balanced and resilient agricultural system.

The application of advanced technologies, such as Agriculture 5.0, which uses robotics and artificial intelligence to improve agricultural productivity, not only optimizes the use of resources but also offers innovative tools to address environmental challenges, demonstrating a commitment to sustainability. Promoting diversified agricultural practices improves soil health and helps mitigate risks associated with climate change and market fluctuations.

Biostimulants are mainly composed of beneficial microorganisms, including various PGPR strains. These microorganisms include genera such as *Bacillus*, *Pseudomonas*, *Azospirillum*, and *Mycobacterium*. These microorganisms perform key functions, such as phosphate solubilization, nitrogen fixation, and the production of plant hormones that stimulate growth. In addition, some can produce siderophores, which help plants absorb iron and other compounds that improve resistance to disease and environmental stress.

CONCLUSIONS

In conclusion, using soil microbiota in agriculture offers multiple benefits, such as increased plant growth and improved soil health, essential for optimal production. Several countries have investigated and applied PGPR on different crops, revealing that each microbial consortium presents variable effectiveness depending on the application conditions. These bacteria protect crops from pathogens and support plant growth and food safety. Correctly applying bacterial consortia can increase production, contribute to food sovereignty, and promote environmentally friendly fertilization techniques. It is essential to integrate agricultural technification in Mexico and develop new sustainable technologies to achieve better yields and minimize the adverse effects of chemical fertilizers. In addition, it is crucial to include information on the impact of microbial inoculants in the digital analysis of Agriculture 5.0 to optimize agricultural yields. These microorganisms improve soil health and nutrient availability, allowing farmers to implement more sustainable and efficient practices, resulting in increased productivity and sustainability in the Mexican agricultural sector.

The integration of Agriculture 5.0 is essential to maximize these benefits; using advanced technologies such as artificial intelligence and data analytics, farmers can optimize PGPR and improve decision-making in real-time. This synergy between biotechnology and digitization will enable more efficient resource management, driving sustainable agricultural practices. Including information on the effect of microbial inoculants in digital analysis is key to optimizing agricultural performance. Together, these approaches improve soil health and nutrient availability and empower farmers to implement more sustainable and efficient practices.

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