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A Narrative Review: Beneficial Microbes for Enhancing Soil Health and Maize Productivity on Marginal Soils

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ABSTRACT

Maize is a vital food and industrial crop, yet its productivity is limited by marginal soils such as acidic, saline, and degraded lands with nutrient deficiencies and low organic matter. Excessive chemical fertilizer use provides short-term yield benefits but degrades soil quality and reduces microbial diversity, creating the need for sustainable alternatives. This article reviews the role of beneficial microbes in improving soil health and maize productivity. A narrative literature review was conducted using publications from 2020 to 2025 to synthesize relevant data and findings. The results shows that PGPR, AMF, cyanobacteria, and endophytic bacteria enhance nutrient cycling, stimulate root growth, and increase tolerance to drought, salinity, and nutrient stress. Integrated use of microbial inoculants with organic and chemical fertilizers improved soil fertility and raised maize yields by up to 85%. Beneficial microbes therefore offer effective, eco-friendly strategies for resilient and sustainable maize production on marginal soils.

KEYWORDS: bioinoculants, nutrient cycling, stress resilience, sustainable agriculture

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INTRODUCTION

Maize (*Zea mays* L.) is a major food crop alongside rice and wheat, playing a strategic role in the economy, particularly in Indonesia. Maize is not only a food source but also a raw material for the animal feed, food, biofuel, and other industries (Grote et al., 2021). Maize is estimated to contribute 42% of the world's food calories and 37% of the world's protein intake (FAOStat, 2021). Demand for maize continues to rise, making it economically valuable and with significant potential for further development (Erenstein et al., 2021).

Maize productivity in developing countries, especially in tropical regions, is severely limited by poor soil fertility, which is caused by nutrient depletion and degradation, as well as environmental stresses such as drought, heat, and waterlogging (McLeod et al., 2020). Marginal soils, such as acid soils (ultisols, oxisols), saline soils, and degraded lands, occupy large areas in developing countries and can limit maize productivity due to nutrient deficiencies, aluminum toxicity, and low organic matter (Alabi et al., 2022). These challenges result in very low maize yields, thereby hindering food security and farmers' incomes.

Conventional agricultural practices, especially the use of large amounts of chemical fertilizers, can produce high yields in the short term but cause soil degradation by reducing soil organic matter, damaging soil microbial communities, and inhibiting the soil's ability to retain water (Kabenomuhangi, 2024). This creates a destructive cycle, where more and more inputs are needed, but the returns are decreasing. In contrast, beneficial microbes are a sustainable agricultural practice because they naturally improve soil health and plant resilience by enhancing nutrient availability through processes like nitrogen fixation and phosphate solubilization, promoting root development, and increasing the soil's ability to withstand stress from conditions such as drought or salinity (Khan et al., 2021). They achieve this by forming symbiotic relationships with plants, producing growth-promoting substances, and creating beneficial soil structures that improve water and nutrient retention (Kumar et al., 2025). This review aims to highlight the role of beneficial microbes in improving soil health and maize productivity in marginal soils, while also discussing challenges, limitations, and future research directions.

MATERIALS AND METHOD

The research method used is a qualitative research method with a narrative literature review. A narrative literature review is a type of qualitative research through a series of activities related to collecting library data, reading, writing, and gathering various research materials. This method aims to compile a summary or review obtained from the results of previous research on a specific topic. Literature search is conducted by searching for secondary data obtained from research results by previous researchers.

Literature search was conducted through an in-depth process of searching for published information on a topic using various information search tools. The criteria for selecting journals were journals related to the role of various beneficial microbes in increasing maize productivity on marginal soils, with a publication period between 2020 and 2025. Data sources were obtained from *Google Scholar* and *ScienceDirect* publications. The selection process was conducted manually by reviewing titles, abstracts, and full texts to ensure relevance to the review topic. Irrelevant, duplicate, or inaccessible articles were not included.

DISCUSSION

Marginal Soils and Their Challenges

Marginal soils are land areas with limitations in their physical, chemical, or biological properties that prevent optimal plant growth. These limitations include acidic conditions, saline or sodic properties, and poor water and nutrient retention, as seen in sandy soils (Hati et al., 2024). Such soils are prevalent in tropical and subtropical regions of Asia, Africa, and Latin America, posing challenges for agriculture, particularly for staple crops like maize. Marginal soils are typically low in essential nutrients such as nitrogen, phosphorus, and potassium. Acid soils are characterized by high aluminum saturation, while saline soils suffer from excessive soluble salts that inhibit root water uptake. Low cation exchange capacity and poor soil structure further reduce nutrient retention and microbial activity, making these soils less responsive to fertilizer inputs (Zydelis et al., 2025). For maize, these constraints manifest as stunted root development, nutrient imbalances, and reduced biomass accumulation, ultimately lowering grain yield. In extreme cases, productivity can drop by 40–60% compared to fertile soils. These limitations highlight the urgent need for soil biological approaches that can sustainably enhance fertility and crop performance (Chernov et al., 2021).

Beneficial Microbes for Soil Health

Plant growth-promoting rhizobacteria (PGPR) are beneficial soil bacteria, such as *Azospirillum*, *Azotobacter*, *Bacillus*, and *Pseudomonas*, that live in the rhizosphere (root zone) and boost plant growth through several mechanisms. They increase nutrient availability by fixing nitrogen, solubilizing phosphate, and producing siderophores for iron uptake, while also producing plant hormones (auxins, gibberellins, cytokinins) to enhance root development and other growth processes. These bacteria improve plant health both directly through nutrient provision and hormone production, and indirectly by suppressing pathogens and helping plants tolerate environmental stresses (Igiehon et al., 2024).

Arbuscular mycorrhizal fungi (AMF) are beneficial soil microbes that form a symbiotic relationship with maize (corn) roots, significantly improving crop growth and resilience. They do this by extending their hyphal networks, which increase the effective root surface area for nutrient and water uptake, and by producing glomalin, a sticky protein that improves soil structure and water retention. These actions make AMF plants more tolerant to environmental stresses like drought, salinity, and nutrient deficiencies, and can reduce the need for chemical fertilizers (Wahab et al., 2023).

Cyanobacteria and soil algae are beneficial microbes in the soil, with cyanobacteria like Anabaena and Nostoc fixing atmospheric nitrogen, which is crucial for soil fertility, and both contributing organic matter and improving soil structure. They enhance degraded lands by increasing water retention and nutrient availability, promoting overall soil health and supporting microbial diversity, especially in low-input agricultural systems (Nawaz et al., 2024).

Endophytic bacteria, including actinomycetes, live inside plant tissues, often without causing harm. They are valuable because they produce antimicrobials and other compounds to suppress pathogens and can also enhance plant growth by aiding in nutrient mobilization, like producing plant hormones. Genera such as Streptomyces, a type of actinomycete, are particularly known for their ability to produce a wide array of bioactive metabolites and contribute to plant health (Aamir et al., 2020).

Mechanisms of Action

Beneficial microbes enhance nutrient availability by performing nitrogen fixation, phosphate solubilization, and mobilizing potassium and micronutrients. Nitrogen-fixing microbes, such as Rhizobium, convert atmospheric nitrogen (N_2) into ammonia (NH_3), which is a form plants can use for growth or plant-available forms (Figiel et al., 2025). Phosphate-solubilizing bacteria and arbuscular mycorrhizal fungi (AMF) increase the availability of insoluble phosphorus, with AMF forming extensive networks that improve uptake efficiency (Laishram et al., 2025). Microbes also release essential minerals like potassium (K) and micronutrients from insoluble compounds in soil by producing organic acids, chelating agents, and enzymes that facilitate acidolysis, chelation, and complexolysis. These biochemical processes break down silicate minerals, converting K and other nutrients into soluble forms that plants can readily absorb, enhancing crop growth and improving soil fertility (Jini et al., 2024).

Microbes facilitate plant growth by producing phytohormones such as auxins that stimulate root development and nutrient absorption, and by inducing induced systemic resistance (ISR) which enhances plant defenses against pathogens (Orozco et al., 2023). Microbes can produce siderophores, which are compounds that chelate iron, making it available to the plant and unavailable to pathogenic fungi. They also improve the solubilization of other essential nutrients (Timofeeva et al., 2022). These plant growth-promoting microorganisms contribute to sustainable agriculture by improving plant health, increasing yields, and reducing the need for chemical inputs like fertilizers and pesticides (Kumar et al., 2022).

Arbuscular mycorrhizal fungi (AMF) improve soil health by producing glomalin, a glycoprotein that binds soil particles together for better structure and water retention (Fall et al., 2022). Additionally, the organic matter from microbial biomass enhances soil fertility by increasing its ability to hold water and nutrients, while microbial antagonism from these beneficial fungi helps to suppress soilborne pathogens, creating a more resilient and healthy soil ecosystem (Matos et al., 2021).

Beneficial microbes enhance plant resilience to environmental stresses by alleviating aluminum and iron toxicity in acidic soils, helping plants adjust osmotically to salinity, and improving water uptake during drought conditions through increased root hydraulic conductivity (Song et al., 2025). This microbial support is essential for maintaining crop yields, particularly for maize in marginal environments.

Application of Beneficial Microbes in Maize Production

Table 1. The Use of Beneficial Microbes in Maize Production on Marginal Soils

Marginal Soil Type	Microbes Used	Key Function	Impact on Maize	Yield Increment (%)
Sandy loam, acidic, nutrient-poor, drought-prone soils	- Plant Growth-Promoting Rhizobacteria (PGPR): *Bacillus, Pseudomonas, Azospirillum, Rhizobium* - Arbuscular Mycorrhizal Fungi (AMF) - Actinomycetes - ACC -deaminase-producing microbes	- Nitrogen fixation, phosphorus solubilization, potassium and micronutrient mobilization - Production of phytohormones (auxins, cytokinins, gibberellins) - Mitigation of abiotic stress (ACC-deaminase) - AMF hyphae enhance water and nutrient uptake - Production of enzymes & metabolites that improve soil structure	- Increased plant height, root biomass, leaf area, and chlorophyll content - Higher water-use efficiency - Improved tolerance to drought stress - Higher yield compared to control	**±30–35%** (depending on microbial combination, PGPR + AMF consortia most effective) (Zhang et al., 2025)
Acidic soils with low fertility	*Bacillus subtilis*, *Bacillus amyloliquefaciens*	Enhance nutrient availability (nitrogen, phosphorus, potassium), produce phytohormones, solubilize phosphate	Increased grain yield, improved dry matter accumulation, and higher nitrogen uptake	Up to 65% higher compared with chemical fertilizer alone (Wang et al., 2025)
Nutrient-poor marginal soils	Beneficial bacterial consortium (*Bacillus* spp.)	Improve soil health, increase efficiency of mineral fertilizers, stimulate root growth	Highest maize productivity achieved through enhanced root growth, nutrient absorption, and drought resilience.	Up to 85% higher compared with chemical fertilizer combined with

Marginal Soil Type	Microbes Used	Key Function	Impact on Maize	Yield Increment (%)
				organic fertilizer (Wang et al., 2025)
Saline soil (high salinity stress)	*Bacillus sp.* PM31 (plant growth-promoting rhizobacteria)	Produces indole-3-acetic acid, siderophores, exopolysaccharides; enhances nutrient uptake (N, P, K); improves antioxidative defense system; promotes osmotic adjustment under stress	Improves seed germination, root–shoot length, chlorophyll content, and relative water content; enhances agro-morphological traits and biomass	Yield increased by **40–50%** under salinity stress compared to control (Ali et al., 2023)

The application of beneficial microbes in maize production is a sustainable approach to improving plant resistance to abiotic stress while supporting productivity on marginal land. Rhizosphere microbes such as Plant Growth-Promoting Rhizobacteria (PGPR) and Arbuscular Mycorrhizal Fungi (AMF) play an important role in improving nutrient uptake, stimulating root growth, and improving plant water status. Table 1 shows that cross-inoculation of the rhizobiome from *Andropogon virginicus*, a native plant of marginal lands, into the maize rhizosphere has been proven to increase microbial diversity and complexity, particularly among fungal groups. This increase in fungal diversity positively correlates with maize's drought tolerance, as evidenced by higher relative leaf water content, reduced ion leakage, and lower H_2O_2 accumulation under dry conditions (Zhang et al., 2025). This confirms that the application of beneficial microbes not only functions as a biofertilizer but also as a bio-inoculant capable of strengthening the plant's physiological system in response to environmental stress. Therefore, the strategy of utilizing rhizosphere microbial consortia from drought-tolerant maize plants holds great potential for enhancing maize productivity on marginal lands in the era of climate change (Zhang et al., 2022; Zhang et al., 2025).

Table 1 shows application of beneficial microbes in maize production plays a crucial role in improving soil fertility and crop performance, particularly in marginal and semi-arid soils. In this study, biofertilizers containing *Bacillus subtilis* and *Bacillus amyloliquefaciens* were applied in combination with chemical and organic fertilizers, and they demonstrated multiple beneficial functions, including nitrogen fixation, phosphate solubilization, decomposition of crop residues, and production of plant growth–promoting hormones. These plant growth–promoting rhizobacteria not only enhanced nutrient availability but also supported root development, improved soil microbial activity, and increased enzymatic processes, which collectively contributed to higher nitrogen uptake, water productivity, and grain yield. The integrated application of chemical fertilizer, organic fertilizer, and biofertilizer was found to be the most effective strategy, with maize yields increasing up to 85% compared to chemical fertilizer alone, highlighting that beneficial microbes are vital for sustaining soil quality and achieving higher productivity under both sufficient and limited water supply conditions (Wang et al., 2025).

Table 1 shows the application of beneficial microbes, particularly plant growth-promoting rhizobacteria (PGPR), plays a vital role in enhancing maize production under marginal soil conditions such as salinity stress. In the study by Ali et al. (2023), inoculation with *Bacillus sp.* PM31 significantly improved agro-morphological traits, including shoot length, root length, plant height, leaf area, and biomass, even under high salinity levels. These improvements were attributed to the bacterium’s ability to produce indole-3-acetic acid, siderophores, exopolysaccharides, and ACC deaminase, which collectively reduced ethylene production, enhanced nutrient uptake, and improved antioxidant activity. Moreover, *Bacillus sp.* PM31 inoculation increased chlorophyll content, relative water content, soluble sugars, proteins, and osmolyte accumulation, while reducing oxidative stress markers such as hydrogen peroxide, malondialdehyde, and electrolyte leakage. Through these mechanisms, the beneficial microbes not only mitigated the negative impacts of salinity but also enhanced maize growth and yield, highlighting their potential as sustainable biofertilizers for improving crop productivity in salt-affected soils (Ali et al., 2023).

Challenges and Limitations

Beneficial microbes for agriculture face challenges including environmental variability affecting survival and colonization, poor shelf-life and storage in regions with limited infrastructure, and inconsistent results across different locations, which can be caused by the complex interactions between the microbial inoculants, the host plant, and the diverse native soil microbiome. These factors contribute to the limited adoption of microbial inoculants by farmers, highlighting the need for more robust solutions in formulation, application, and research to overcome these practical limitations (Diaz et al., 2025).

Barriers to biofertilizer use include a lack of farmer awareness and insufficient promotion, the limited availability of high-quality inoculants, and the absence of standardized quality assurance protocols and government regulation to build farmer trust and ensure product effectiveness. Addressing these market and policy challenges requires targeted farmer training, improved availability and quality of biofertilizers, and the establishment of clear legal and quality frameworks for the industry (Hasan et al., 2025).

Future Perspectives

Future research should concentrate on creating synthetic microbial consortia (SynComs) with multiple functions, such as improved nutrient mobilization, stress resistance, and pathogen control, by integrating biotechnology and genetic engineering. Advances in synthetic biology and multi-omics technologies will enable the design of more efficient and resilient SynComs tailored for specific plants and conditions, promoting sustainable agriculture by reducing reliance on chemicals and enhancing crop health and productivity (Tariq et al., 2025).

Integrating microbial technologies with precision agriculture offers site-specific, targeted applications of beneficial microbes to enhance maize production by improving nutrient availability and soil health. To overcome adoption challenges, government support through biofertilizer subsidies and robust farmer training programs is crucial, especially for sustainable maize cultivation on marginal lands. This approach leverages technologies like drones and data analytics to optimize microbial delivery and survival, leading to increased crop productivity and resilience while reducing reliance on synthetic fertilizers and promoting long-term soil health and environmental sustainability (Cruz and Dias, 2023).

CONCLUSION

Beneficial microbes play a crucial role in enhancing soil health and maize productivity, particularly on marginal soils where chemical fertilizers alone are insufficient and unsustainable. Evidence shows that plant growth-promoting rhizobacteria (PGPR), arbuscular mycorrhizal fungi (AMF), cyanobacteria, and endophytic bacteria can improve nutrient cycling, stimulate root development, strengthen stress tolerance, and restore soil fertility, thereby increasing maize yields by up to 85% when integrated with organic and chemical fertilizers. Despite their proven potential, challenges such as environmental variability, inconsistent field performance, limited product availability, and weak regulatory frameworks hinder widespread adoption. Addressing these barriers through improved microbial formulations, farmer training, and supportive government policies is essential. Future research focusing on synthetic microbial consortia and integration with precision agriculture offers promising pathways for scaling up microbial technologies. Overall, beneficial microbes represent an eco-friendly, cost-effective, and sustainable strategy to strengthen resilience and productivity of maize grown on marginal soils in the context of climate change.

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