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The Application of Microbial Inoculants as a Green Tool towards Achieving Sustainable Agriculture

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Abstract

For decades, the surging demand for agricultural produce to alleviate hunger has spurred extensive research into novel and sustainable agricultural practices. Given the detrimental environmental impact of some contemporary agricultural methods, this paper underscores the potential of microbial inoculants as environmentally friendly tools for achieving sustainable agriculture. This narrative review evaluates the use of microbial inoculants in various agricultural practices such as monocropping, crop rotation, and intercropping, contrasts their effectiveness to synthetic agricultural compounds, and highlights potential limitations and strategies for their mitigation. The review reveals that microbial inoculants, as renewable, eco-friendly, crop-supportive, and cost-effective alternatives to synthetic agricultural compounds, hold immense promise for sustainable agriculture. The study concludes with a call for greater emphasis on the use of microbial inoculants, encouraging their broader adoption by farmers to promote sustainability in agriculture.

Keywords: *Microbial inoculants, Microorganisms, Sustainable agriculture, green tool, Agricultural practices*

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Introduction

The burgeoning world population demands an increase in food supply, a challenge that has left over 850 million people globally suffering from chronic hunger [1]. As part of the solution, microbial inoculants, a sustainable technology, promises to enhance soil health and crop yield [2]. These beneficial microorganisms (Table 1), also known as bioinoculants or Plant Growth-Promoting Microorganisms (PGPM), boost nutrient absorption, pest control, pathogen management, and provide resilience against abiotic stress factors [2, 4].

Agricultural practices, such as monocropping, intercropping, and crop rotation, can substantially benefit from microbial inoculation. However, monoculture may promote intensive herbicide use, leading to weed resistance and water pollution, contrasting with the biodiversity fostered by intercropping or crop rotation [12]. The principal elements of agricultural soils, Nitrogen (N), Potassium (K), and Phosphorus (P), are supplied through organic farming and traditional cropping systems [6]. Compost and crop rotation serve similar purposes, enhancing indigenous microbial communities [5]. Borah et al. found that various microbial cultures significantly increased the microbial population but had little impact on the nutritional component of N, K, and P in vermicompost and farmyard manure [7].

Long-term crop rotation positively influences Carbon dioxide (CO2) emissions and earthworm populations, essential factors for plant growth [8]. It encourages the efficient use of soil nutrients, reduces pest and pathogen prevalence, enriches soil and plant yield, and prevents land degradation [9]. Intercropping, another advantageous agricultural practice, fosters organic matter decomposition and nitrogen-fixing [10]. It serves as an effective management strategy for soil-borne pathogens, akin to microbial inoculations [11]. Furthermore, soil enrichment through intercropping of grain plants has been observed, thereby enhancing soil microbiome and microbial diversity [12, 13]. Given the substantial changes microbial inoculations introduce to soil microbial communities [14, 15], careful observation and monitoring are required to maintain a balance of beneficial microbes and nutrient levels [10]. As we pursue sustainable agriculture, this balance emerges as a critical facet to be carefully managed.

Table 1: Microbial Inoculants employed in agricultural practices field and experimented settings

S/N	Microbial Inoculants	Plant(s) or Crop(s) Involved	Associated Agricultural Practices	References
1	Zinc-solubilizing bacteria (*Gluconacetobacter*, *Bacillus*., *Pseudomonas*)	Legumes and Wheat	Crop Rotation and Intercropping	[16]
2	Seed inoculated Soybean (Bacterium *Azospirillum)*	Soybean	Intercropping	[17]
3	Plant growth-promoting rhizo-bacteria (PGPR) for legume-based	Maize (*Zea mays*)/ Soybean (*Glycine max*) Proso millet (*Panicum miliaceum* L.) / Mung bean (*Vigna radiata*)	Intercropping	[18]
4	Endophytic Bacteria (SaMR12)	Eggplant (*Solanum melongena* L.)	Intercropping	[19]
5	*Azospirillum* combined with nitrogen fertilization	Sorghum	Intercropping	[20]
6	*Mycorrhizosphere bacteria* (arbuscular mycorrhizal fungi (*Rhizophagus irregularis*) for Cereal-legume based	Maize (Corn)	Intercropping	[21]
7	Rhizobium-inoculated maize	Maize (*Zea mays* L.)/ Faba bean (*Vicia faba* L.)	Intercropping	[22]
8	*Urochloa brizantha and sorghum inoculated with Azospirillum brasilense for silage*	Sorghum seed	Intercropping	[23]
9	Arbuscular mycorrhizal fungi (AMF) and plant growth-promoting rhizobacteria (*Pseudomonas*)	Pigeon pea (*Cajanus cajan*) and finger millet (*Eleusine coracana*)	Intercropping	[24]

Comparative Effectiveness of Microbial Inoculants on Soil Biotic and Abiotic Factors

As alternatives to synthetic agricultural chemicals, microbial inoculants offer several benefits. They serve as renewable, eco-friendly nutrient sources that invigorate soil biology and replenish soil fertility [25, 26]. Capable of mitigating agricultural diseases and abiotic stressors, microbes contribute to numerous environmental biological and chemical processes, including pathogen biological control and nutrient cycling, consequently enhancing nutrient availability [27, 28, 29]. Microbial inoculants foster biodiversity, creating conducive conditions for beneficial microorganisms' growth and improving soil physical properties [30]. These improvements include enhancing soil particle structure and aggregation, reducing soil compaction, increasing pore spaces, and fostering water infiltration.

In soils contaminated with toxins, xenobiotics, and refractory chemicals, microbial inoculation facilitates the biodegradation of complex substances and initiates bioremediation processes [30]. Microbial inoculants also promote resistance to diseases, proving useful for biological plant disease control [31], weed pest management (biological herbicides) [32], and insect pest control (biological insecticides) [33]. Their antioxidant properties boost the decomposition of organic matter and increase soil humus content, positioning them as viable alternatives to chemical agriculture [34]. Microbial inoculation stands as a cost-effective solution to soil salinity stress [35]. It helps plants manage this stress by enhancing nutrient uptake, triggering an antioxidative defense mechanism, modulating plant hormone levels, and reducing ethylene levels by producing 1-aminocyclopropane-1-carboxylatedeaminase in the plant's rhizosphere [30].

Abiotic stressors like salinity, drought, floods, and acidity constitute significant challenges in agriculture, rendering considerable agricultural land unproductive [36]. Microbial-derived substances can significantly reduce these abiotic stress effects. For instance, long-chained Acyl homoserine lactone (AHL) compounds produced by *Burkholderia graminis* improve tomato growth and salt tolerance [37], while siderophores synthesized by *Streptomyces acidiscabies* E13 mitigate metal-induced oxidative stress in cowpea plants [38].

However, the application of microbial inoculants can occasionally lead to unintended outcomes. The introduction of *Fusarium* and *Rhizoctonia* strains for controlling invasive weeds may inadvertently suppress native plant species through interactions with root-disrupting insects and the prevalence of other potentially growth-suppressive microorganisms [39]. Additionally, microbial invasion can affect the genetic diversity of indigenous resident populations through interactions and horizontal gene transfers (HGT) that favor genetic alterations [40].

In the face of biotic stress, biological control has been an effective agricultural strategy. Some substances can directly inhibit plant diseases [41], enhance systemic resistance [42], or promote soil fungistatic and suppressiveness [43]. For example, maize plants treated with 2,3-butanediol exhibited heightened resistance to *Setosphaeria turcica*, the fungus causing Northern corn leaf blight [44]. Other substances may improve nutrient availability for plant uptake [45] or stimulate the production of advantageous secondary metabolites in the plant [46], allowing it to flourish despite biotic stress.

Farmer Accessibility and Benefits of Microbial Inoculants

Research by Doss [47] indicates that institutional factors such as policy influence the availability and accessibility of inputs, markets, and credit facilities that support inoculant technology use. Llewellyn's study [48] revealed that innovations' adoption was hindered due to extension agents' inability to reach farmers promptly due to poor transportation, adverse weather conditions, and other technical difficulties. Further, Anang's questionnaire study [49] enumerated issues contributing to the reduced accessibility of inoculants: their perishability, lack of easy access, insufficient funding for purchase, inadequate information, absence of refrigeration for storage, lack of available inoculants, and complex technical procedures. These observations align with Dogbe's [50] assertion that the inability of farmers to access funds for agricultural inputs is a significant hindrance to African agricultural development. Callaghan [51] also notes the high cost of maintaining both seed and microbial viability during storage.

The use of microorganisms for soil bioremediation has numerous benefits, including their ability to sequester heavy metals, recycle nutrients, and decompose pollutants [52]. *Arbuscular mycorrhizal* fungi (AMF), a widely-used fungal biofertilizer, can be incorporated for this purpose [53], as their external hyphae contribute to plant uptake of immobile nutrients and alleviate heavy metal toxicity [54]. Plants provide microorganisms with root exudates like proteins, vitamins, and hormones, thereby protecting plant roots from direct contact with contaminants [55].

Commonly utilized inoculants on crops include *Rhizobium*, *Azospirillum*, and *Bacillus* [56]. Rhizobium is considered safe and enhances plant growth through nitrogen fixation, phosphate solubilization, pathogen inhibition, and stress resistance [57]. *Azospirillum* promotes plant growth by releasing secondary compounds like amino acids, indole acetic acid, cytokines, and polyamines, favoring root growth and improved water and nutrient absorption [58, 59]. Bacillus is known for its production of lipopeptides, lytic enzymes, and endotoxins that exert biological control against pathogens affecting corn, wheat, and fruit trees [60, 61, 62]. Certain Bacillus strains are also recognized for hormone production and phosphate solubilization [63].

In a move to mimic soil communities, newer inoculants contain multiple species [64], recognizing that microorganisms are found in communities and not in isolation. Co-inoculation of Plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF) is considered an additive strategy among biofertilizers [65].

Challenges in Utilizing Microbial Inoculants for Enhancing Agricultural Sustainability

Various abiotic environmental parameters profoundly influence the effectiveness of microbial inoculant applications. These include factors such as light intensity, temperature, pH, soil type, and the nutrient and rare element content [66]. These parameters, combined with the biotic component, can impact not just the applied microorganisms but also the entire holobiont - the host (crop) plant and its associated macro- and microbiota, consequently affecting the overall performance of the applied microorganisms [67].

Although microbial strains selected for a specific purpose often show promising results in controlled greenhouse trials, even when non-sterile soil is used, their effectiveness can be unpredictable and inconsistent in the field, limiting the practical application of these microbial solutions [67]. This inconsistency calls for innovative solutions [66]. Factors such as physiological activity, initial cell dosage, compatibility with the target plant, and the recipient environment's abiotic and biotic characteristics may influence strain establishment. The prevailing conditions of the soil/plant environment, typically overlooked during microorganism cultivation, may affect the introduced strain's competitive ability and limit its establishment. The inoculated microorganisms must compete with a diverse range of existing microbiota [67].

The specificity of microbial inoculants presents a critical obstacle to their wider adoption. Unlike agrochemicals, which typically have broad-spectrum effects on numerous organisms, microbial inoculants are often highly specific [66]. For instance, carboline, a compound produced by *Elytrigia repens*, enhanced aphid resistance in barley [68]; however, its effectiveness diminished in the absence of barley. In complex field environments, where multiple factors operate concurrently, this specificity can lead to variable outcomes in terms of quality and efficacy [66].

The process of isolating, identifying, and purifying certain compounds is time-consuming and labor-intensive. The volatile nature of some compounds [69, 70] necessitates the use of sophisticated and potentially expensive isolation techniques. Abnormal levels, particularly high concentrations of some compounds, can inhibit rather than promote plant growth [71]. For example, Lo Cantore et al. [71] observed that DMDS at 2.5 µg inhibited broccoli and lettuce seed germination, while lower doses of 0.312 and 0.625 µg improved growth. Interestingly, the same substance produced by different microbes can have varying effects on plants. While Vaishnav et al. [72] reported improved germination of soybean seeds treated with 50–100 µg of 1-undecene from Pseudomonas simiae, Lo Cantore et al. [71] and Briard et al. [73] observed negative effects on the germination of broccoli and lettuce seeds treated with the same volatile organic compounds produced by *Pseudomonas aeruginosa*.

Methodology

This study employed Google Scholar and Scopus scientific databases to gather relevant data. The primary focus was on articles published no later than 2003 due to their relevancy to the topic. Nonetheless, a few older articles were also considered given their significance to the study. Irrelevant articles were excluded from consideration. Specific keywords related to the project title were utilized as search queries in these scientific databases, the resulting articles then provided the basis for this narrative review and enabled the construction of evidence-based results.

Discussion and review of evidence

As delineated in Table 2, the findings from this study suggest that specific microorganisms, encompassing fungi, bacteria, nematodes, protozoa, and actinomycetes, can be effectively used as microbial inoculants for the benefit of plants. These microorganisms, and their numerous benefits, which are detailed in Table 2, have been shown to have a positive influence on soil and plant health. Tables 3 and 4 illustrate the manifold advantages of microbial inoculants over synthetic agricultural compounds and demonstrate the effects of soil's abiotic and biotic parameters on the functionality of microbial inoculants. These insights can serve as a valuable contribution to the evaluation and refinement of current agricultural practices on a global scale.

Just as different crops have their unique growth requirements, so do various microbial inoculants have specific prerequisites that can impact their efficiency, as represented in Table 4. This information can be leveraged by farmers and cultivators to foster sustainable agricultural practices.

Nonetheless, as indicated in Table 5, there are certain limitations associated with the use of microbial inoculants with specific plants. These limitations can affect either the availability of inoculants to plants or the accessibility of the inoculants to the plants. Hence, to achieve sustainable agriculture, it is crucial to take into account factors such as the type of soil, its biotic and abiotic elements, the plant species of interest, and the choice of microbial inoculants.

Table 2: Benefits of Microorganisms

Study	**Microorganisms**	**Examples of microorganism**	**Benefits**
[74]	Fungi	Arbuscular Mycorrhizal (AM)	They produce iron (Fe) and other micronutrients
[75]	,,	,,	Make plants more resistant to saline conditions
[76]	,,	,,	They produce phyto-hormones that stimulates the plants to release chemicals that will inhibit or hinder the growth of pests and diseases
[77]	,,	,,	They network with other neighbouring plants including plants of different species by transferring nutrients and resistance to infestations of pests and diseases thereby, enhancing yields of multi-cropping systems
[78]	Bacteria	Agrobacterium	Enhance nodules and solubilize phosphorus
[75]	,,	Azotobacter	Fixes nitrogen, solubilize phosphorus and tolerance for drought salinity
[78, 79, 80]	,,	Bacillus	Fixes nitrogen Enhance nodules Enhance crop growth Solubilizes phosphorus Responsible for Potassium uptake Suppresses diseases
[80, 81, 82]	,,	Rhizobium	Fixes nitrogen Solubilizes phosphorus Tolerance for drought salinity Suppresses diseases
[82, 83]	,,	Azoarcus, Diazotrophicus, Herbaspirillum and Serratia	They all help in fixing nitrogen in the soil
[84]	Actinomycetes		They recycle organic matters in the environment by producing hydrolytic enzymes
[85]	Protozoa		Protozoa increases plant biomass independently of nutrient contents in plant tissue
[86]	,,		Protozoa can stimulate bacterial production of secondary metabolites
[87]	Nematodes		They affect the growth and metabolic activities of microbes thereby regulating rates of decomposition
[88, 89]	,,		They play an important role in nitrogen cycle by mineralizing nitrogen to release excessive ammonium NH_4^+
[88]	,,		They regulate bacteria population and community composition
[90]	,,		Nematodes enhance soil quality by providing food sources for other organisms and consume disease causing organisms
[90]	,,		They are an important resource in battling soil borne diseases

Table 3: Some advantages of Microbial Inoculants over Synthetic agricultural chemical

S/N	Comparing factor		Effect(s)	Reference(s)
1	Soil Quality	Microbial Inoculant	Antioxidant activities of microbes encourage the breakdown of organic materials and boost the soil's humus level; soil particle structure and aggregation are improved, compaction is decreased, pore spaces are increased, and water infiltration is increased.	[91, 92]
		Synthetic agricultural chemical	Long-term use of agrochemicals in agriculture may have harmful effects on soil processes, soil microbial activity, soil nutrient cycling, and crop yield. Numerous synthetic fertilizers contain acid radicals like HCl and sulfuric radicals, which raise soil acidity and negatively impact the health of the soil and plants.	[93, 94]
2	Soil biodiversity	Microbial Inoculant	It aids conservation or restoration of biodiversity	[95, 96]
		Synthetic agricultural chemical	The use of herbicides and synthetic fertilizers alters the interconnections between below-ground and above-ground ecosystems, disrupts internal biological cycles, and impairs pest management.	[97]
3	Aquatic Environments	Microbial Inoculant	Application of microbial Inoculant reduces the use of agrochemicals, thereby reducing waste and pollution	[98]
		Synthetic agricultural chemical	Natural resources, especially groundwater and water used for aquaculture, are compromised by the presence of chemical residues. Toxic pesticides, herbicides, and chemical fertilizers used in agriculture contaminate water sources.	[99, 100, 101, 102]
4	Food Quality and safety	Microbial Inoculant	Biofertilizers, made up of active microbes, are a viable alternative technology to increase food production without jeopardizing human and environmental health. Biofertilizers improve the nutritious properties of fresh vegetables by increasing; the antioxidant activity, the total phenolic compounds and chlorophyll.	[30, 103]
		Synthetic agricultural chemical	Human cancer, obesity, endocrine disruption, and other disorders have been linked to pesticide and synthetic chemical exposure.	[104, 105, 106]

Table 4: Effects of soil abiotic and biotic parameters on microbial inoculants

Table 4: Effects of soil abiotic and biotic parameters on microbial inoculants (Cont'd				
S/N	**Soil parameters**	**Class of parameter**	**Study**	**Effects on Microbial inoculants**
1	Soil Texture	Abiotic	[107]	Inoculants survive better in fine-textured (clay) soils than in coarse (sandy) soils.
2	Soil Moisture	Abiotic	[108]	The volume of percolating water introduced to a root system affects the depth of bacterial colonization of the rhizosphere.
			[107]	Predation would be more accessible to bacterial cells introduced into first moist soil than to cells introduced into initially dry soil.
3	Nutrient Components	Abiotic	[107]	Due to the scarcity of available nutrient sources to microbes in soil, the population sizes of PGPMs decrease more or less rapidly after introduction into natural soil.
			[109]	The addition of enrichment materials can improve the performance of bioformulations.
4	Osmotic Stress	Abiotic	[110]	Salinity has a deleterious influence on the long-term viability of essential microorganisms found in the rhizosphere of plants. With increased osmotic stress, there decrease in the synthesis of plant growth-promoting and biocontrol metabolites have been reported.

Table 4: (Cont'd)

			[111, 112]	Increased salinity has been shown to inhibit the survival and development of Rhizobium strains.
			[113]	Increased salinity can result in a drop in ergosterol content, indicating that fungal abundance reduced.
5	Soil Acidity and Alkalinity	Abiotic	[114]	Phenazine-1-carboxamide have been reported to have ten times the antifungal activity of phenazine-1-carboxylic acid in vitro at pH 5.7. (PCA).
			[115]	In vitro, the activity of 2,4-DAPG against Pythium species have been reported to be higher at acidic pH than at neutral to alkaline pH.
6	Temperature	Abiotic	[116]	The concentration of DAPG accumulated at 18 °C in P. fluorescens CHA0 have been reported to double up at 30 °C.
			[117]	Fungal and bacterial growth rates were reported to be reduced at higher temperatures.
7	Soil Amendment with Agrochemicals	Abiotic	[118]	Compared to the control, the nitrogenase activity of *S. meliloti* was reported to decrease by 93 percent in the presence of carbendazim and thiram, and by 91 percent in the presence of imazethapyr.
			[119]	P fertilizer can reduce the number of mycorrhizal fungi.
8	Soil Indigenous Microbes	Biotic	[120]	The inoculation of bacteria on maize growth can be influenced favourably by the promotion of native microflora.
			[121]	The use of Azotobacter chroococcum and Azospirillum brasilense in maize can enhance the population of actinomycetes.

Table 5: Factors influencing the availability and accessibility of microbial inoculants to plants and soil

Study	**Factor**	**Effects**
[122]	In-field competition	For introduced microorganisms to persist in the following growing seasons, they need to benefit the soil preferentially and outcompete the microorganisms already in the field.
[123, 124]	Climate change	Microbial inoculants are less effective in areas with increasing temperatures, salinity, poor nutrient and water stressed soil. Climate changes may also decrease the available areas of cultivation. However, certain Plant Growth Promoting Rhizobacteria can correct these.
[125, 51]	Monetary factor	Inoculant's production needs to maintain cell viability for a long period. However, high production cost requiring specialized equipment and skilled labor is a major challenge in the lyophilization processes involving the removal of intracellular water and prolonging microbial lifetime. The cost of maintaining the viability of both seeds and microbes in storage is quite alarming.
[125, 127, 128,]	Microbial threat	The use of microbial inoculant has been reported risky, this is because some microbial biocontrol agents are toxic to non-targeted organisms. Some requirements are needed to be followed under specific conditions to prevent plant, humans and animal pathogens that are found as predominant microbes in products which may jeopardize high quality of beneficial produce.
[128]	Plant/Microbial compatibility	For an inoculant to be effective, it has to be compatible with the plant populations, soil conditions and other existing microbial populations
[128]	Microbial diversity	A particular soil may lack the plant and microbial diversity necessary to respond to an inoculant. Plant species has different chemicals, releases different nutrients into the soil after decomposition which may provide a different type of microbial habitat within its rhizosphere

Conclusion and Recommendations

Given the pressing need for environmentally-conscious practices that minimize adverse global effects, this study emphatically presents microbial inoculants as green tools poised to catalyze sustainable agriculture. When properly studied and harnessed, these bioresources offer immense potential in enhancing agricultural productivity while mitigating environmental impact.

However, the successful implementation of these tools necessitates a collective approach. Governments, research institutions, and relevant stakeholders should align their efforts towards creating awareness, improving accessibility, and ensuring the effective delivery of microbial inoculants to farmers and cultivators. These efforts should be supplemented with continuous research and development aimed at overcoming the existing limitations and enhancing the efficacy of these inoculants.

Furthermore, farmers should be provided with adequate training and resources to effectively integrate the use of microbial inoculants into their farming practices. This would not only improve their productivity but also contribute significantly towards the broader goal of sustainable agriculture.

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Conflicts of interest

The authors declare no conflict of interest

Ethics approval

Not applicable

Authors' contributions

Goshen David Miteu conceptualized the topic/idea, wrote, revised and approved the manuscript. All other listed co-authors equally participated in writing and approving the manuscript.

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