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Application of microbial groups as biological pesticides in comprehensive pest management for optimal and sustainable farming practices with biotechnology

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Abstract

Objective

Agricultural productivity is currently facing a tendency down due to the Earth's fertility and incorrect agricultural practices. More dependence on synthetic chemical fertilizers not only accelerates erosion of soil, but also increases severe environmental and human health problems. The aim of this study is to improve the crop yield, restore earth health and promote environmental agricultural practices, especially Biofertilizers (BF) and biopesticides (BP). The purpose of this research is to check their efficiency to increase the capacity of bacterial inoculants as a biofertilizers and their efficiency in increasing the performance of the crop.

Materials and methods

A field -based experimental study was conducted to evaluate the effect of inoculator of bacteria on the Earth's fertility and crop dividend. The selected biofertilizers included nitrogen fixation and phosphate-solubilizing bacterial strains. These were used to test the plots that grow often cultivated crops below different levels of organic and inorganic entrances. Control plot used traditional chemical fertilizers. Parameters such as the Earth's nutritional conditions, growth speeds, dividends and pest resistance were monitored throughout the season. East and subsequent erosion of soil samples were analyzed to assess changes in nutritional content and microbial activity. The statistical analysis of data was done to compare the treatment effect.

Results

Conclusions reveal a significant improvement in crop dividends and the soil's fertility in plots treated with a biofertilizers compared to those who are only treated with chemical fertilizers. Applications of bacterial inoculants increased nutrients, increased biomass production and improved microbial diversity of soil. In addition, the use of biofertilizers reduced the dependence of synthetic input, contributing to a more durable and environmentally friendly agricultural practice. The plague occurrence in biofertilizers -Credited plots was also low, indicating a collective effect with biopics times.

Conclusions

This study emphasizes the promising role of biofertilizers and biopesticides in sustainable agriculture. Their application not only improves crop and soil, but also reduces environmental impact and production costs. Biotechnology, especially as microbial inoculants, has enormous ability to support global food security. However, in order to fully utilize the benefits, extensive biosecurity rules and peasant training and support systems must be implemented. Integration of biobased solutions into mainstream agriculture can orbit the passage required for long -term agricultural stability for low entrance agricultural systems.

Keywords: Biopesticides, chemical pesticides, microbial groups, pest management, sustainable farming

Paper Type: Review Paper.

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Introduction

The reliance on chemical fertilizers and pesticides in traditional agriculture has increased significantly due to the growing population and rising food demand (Elnahal et al., 2022). Plant nutrition significantly contributes to the increasing food demand (Kumari et al., 2022). to meet this demand, commercial synthetic fertilizers particularly those containing nitrogen, phosphorus, and potassium have played a major role in enhancing crop yields. However, their increasing costs, along with excessive usage, have contributed to soil degradation, loss of biodiversity, environmental pollution, and adverse effects on human health. The overuse of chemical pesticides will harm soil fertility and crop productivity. To address these challenges, biofertilizers biological substance that promote plant growth by enhancing nutrient availability are being considered as a more sustainable and environmentally friendly alternative. Top soil and infertile soil degradation, diminished plant development, lowered yield index, and progressive decline of indigenous microbial communities are mitigated by applying microbial inoculants in agricultural practices (Sivaram et al., 2023). Pesticides are toxic, and synthetic fertilizers generate environmental problems that inoculants from microbial material effectively address, presenting a viable alternative to psychostimulants. Biotechnology (BT) is the extensive field of biology that utilizes living things and creatures to create or produce products. It is "any technological use employing organisms, biological systems, or their by-products to manufacture or alter products or processes for designated purposes." In insect management, it can be described as the intentional and systematic manipulation of biological processes to control insect pests effectively. Living things have developed a vast array of biological capacities, and by selecting suitable organisms with specific characteristics, it is feasible to control insect diseases effectively. BT possesses significant potential to deliver sustained biological components for Integrated Pest Management (IPM) (Jan et al., 2025). Agricultural BT variants serve as a mechanism for studies on agriculture, involving the gene transmission of agronomic significance (and, thus, of preferred traits) from a donor entity (which may include a plant, bacteria, fungi, etc.) to plants, conducted safely (Mohammadabadi et al., 2024a). The advent of contemporary BT signifies a new agricultural phase. Advancements in plant genetics mitigate the reliance on physical and chemical technologies in agriculture. Contemporary BT may enhance efficiency, reduce production costs, improve food quality, and foster environmentally sustainable growth. Sustainable Agriculture (SA) is a method that enhances food production while preserving the indigenous soil bacteria (Rehman et al., 2022). Microbial fertilizers are essential to SA (Bamdad et al., 2022). The application of microbe inoculants is contingent upon the soil profile since they supply a diverse array of micronutrients via natural nitrogen fixation, synthesize hormones for plants, and produce antimicrobial agents, enhancing the availability of essential elements such as potassium and

phosphorus. Over the past decade of studies on microbes and their impact on soil, it has been demonstrated that microbes positively influence the prevention of soil-borne illnesses and enhance soil nutrients, significantly benefiting agricultural productivity. Microbial inoculants consist of active or dormant microbes, including algae, fungi, bacteria, and actinomycetes, occurring singularly or in mixtures. The prevalent bacteria that enhance plant growth are *Rhizobium*, *Azospirillum*, *Trichoderma*, *Pseudomonas*, Acinetobacter, and *Bacillus*, whereas the notable fungal species that support plants include the Mycorrhizal fungi. Microbial inoculations, such as Plant Growth-Promoting Microbes (PGPMs) (Cantabella et al., 2022), significantly enhance the development of plants and agricultural productivity. They facilitate nitrogen fixation from the air in the application process, enhance soil nutrient mobilization, synthesize plant hormones, and safeguard plants from phytopathogenic Microorganisms (MO). Using microbial inoculants for an environmentally friendly system significantly impacts the oversight of combined nutrient networks and sustained agricultural output. Microbial inoculations or BFs comprise live MOs that inhabit the rhizosphere and facilitate plant development enhancement. The process transforms insoluble soil components into a soluble state by a biological mechanism akin to rock phosphate dissolution and fixing nitrogen. Beneficial microbes in BFs enhance microflora, soil wellness, plant development, disease management, and insect protection. BFs contain advantageous microbial inoculants, including nitrogen fixers, phosphorus, sulfur, zinc solubilizers, and crop growth-promoting bacterial species (Samantaray et al., 2024). Plant Growth-Promoting Rhizobacteria (PGPR) are MOs that inhabit the rhizosphere soil and enhance plant development (Khan et al., 2021). They function as chemical pesticides, relying on the capabilities or behaviors of the plants and biocontrol substances. Biopesticide (BP) denotes the utilization of advantageous MOs for controlling insects. The primary limitation is the accessibility of BPs to the total cultivated area. Particular pesticides originating from natural substances function as BPs, including those from vegetation, livestock, microbes, and specific metals. BPs are categorized into three primary types: biochemical, plant, and microbiological. Ninety percent of all BP is applied globally. *Bacillus thuringiensis* (Bt) is the most profitable BP (Li et al., 2022). Contemporary agriculture needs BPs and BFs to meet the growing need for safe, residue-free cultivation of crops. Governmental and non-governmental organizations must assist businesses in developing BFs and chemical pesticides. This review aims to enhance the development and production of plants through diverse microbial inoculants, including bacteria, fungi, viruses, and algae, utilized as BFs, PGPR (Santoyo et al., 2021) such as phosphate solubilizers, nitrogen fixers, chemical messengers, siderophores, and antimicrobial agents, as well as BPs encompassing MOs, plant-incorporated security, and biochemical agents.

Biotechnology for integrated pest management

The IPM principle depends on combining conventional and economical strategies to mitigate insect damage while minimizing risks to humans and the natural world, all without significantly compromising crop yields. The Economic Injury Level (EIL) is the minimum pest density that causes economic harm to crops. To mitigate and prevent financial damages, it is advisable to implement pest control before reaching the EIL. Pest treatment is feasible only when pest proliferation meets or exceeds the Economic Threshold (ET). ET is needed to inhibit pest proliferation before attaining the EL (Angon et al., 2023). Suitable preventative measures must be implemented upon reaching the economic threshold to avert financial losses resulting from pest density or damage. The ET is frequently established at 55%-85% below the EL, ensuring farmers use such ETs with minimal economic and production loss risk. Creating and deploying ETs and more straightforward and effective pest sampling procedures contribute to improving contemporary IPM (Naranjo, 2010). Excessive pesticide uses to protect crops from pests adversely affects health and the state of the planet. The availability of commercially produced chemical pesticides streamlines the farming system and crop protection techniques (Popp et al., 2013). This strategy raises concerns for the future preservation of crops, whereas contemporary IPM practices eschew chemical pesticides, promoting SA. Contemporary IPM depends on the prudent administration of pesticides alongside diverse IPM measures, including utilizing resistant crop types and augmented biological management techniques. By integrating the strategies above at various stages, one substantially attains control of pests and averts yield losses. The current tendency regards IPM as an efficient option for pest control, integrating cultural, natural, and chemical treatments, as shown in Figure 1.

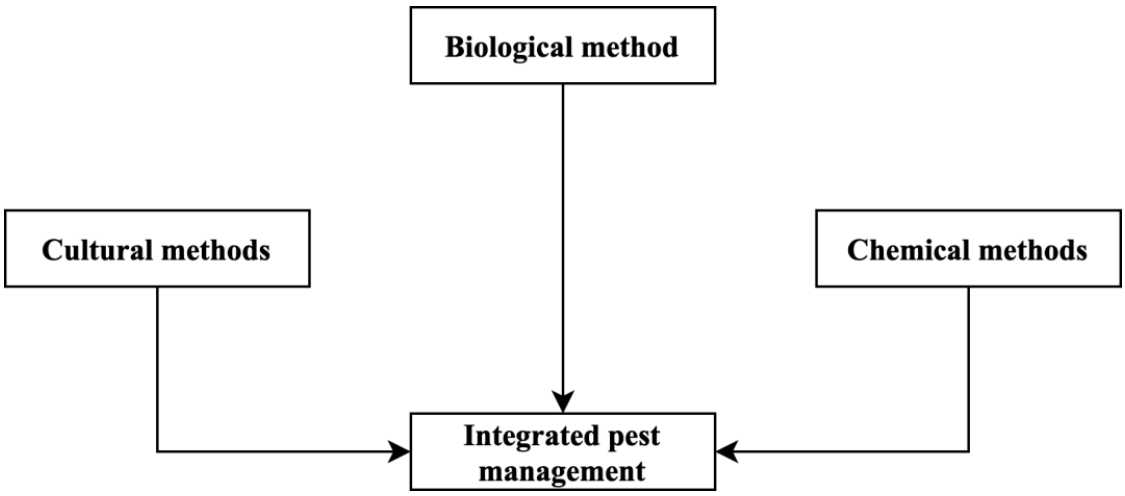

Figure 1. Integrated pest management (IPM) framework incorporating biological, cultural, and chemical control methods

The utilization of BT in IPM can be classified into two main groups: (i) traditional BT and (ii) advanced BT. The present paper is distinctive since it thoroughly examines the extensive application of these two overarching areas of BT in IPM. The application encompasses traditional management strategies (non-transgenic or those that do not include gene transfers) to delineate the most advanced BT IPM alternatives based on DNA breeding and genetic engineering methodologies (Shelton et al., 2002; Romeis et al., 2006). Every treatment is referenced throughout the three pests (diseases, bugs, and herbicides) in a matrix format, thereby updating prior individual studies and facilitating a concurrent comprehension of applications for improved deployment strategies. Traditional BT goods or non-transgenic techniques for IPM encompass a comprehensive array of bio-agents, cell culture methods, and biofertilizers (Deguine et al., 2021).

Biological agents utilized for IPM: Bio-agents encompass various biological substances, including microbiological agents, enemies of nature, parasites, and botanicals. Multiple categories of biocontrol substances and biopesticides, often used together, have been employed as traditional BT solutions for controlling pests. These insect-control agents consist of either bio-agents or their second-generation metabolites. These parts may be utilized individually or in conjunction to optimize the advantages sustainably.

Strategies for IPM: The biological control techniques can achieve greater sustainability, significantly contributing to developing practical and comprehensive IPM approaches to maintain agricultural productivity. IPM is an ecologically-oriented strategy that amalgamates all suitable techniques into a systematic framework to mitigate pest harm (Kogan, 1998). It is internationally recognized as the future paradigm, advocating for the integration of six components: (i) biological management, (ii) host plant opposition, (iii) cultural management, (iv) mechanical and physical management, (v) chemical management, and (vi) regulatory oversight (Ehler, 2006). IPM prioritizes cultivating robust plants while minimizing agroecosystem disturbance and promotes natural IPM.

Tissue culture methodologies: The bulk manufacturing of disease-free seeds through plant tissue cultivation methods transforms methods for controlling pests related to plant host resistance. Tissue Culture (TC) techniques enable the swift propagation of disease-free plants in regulated and sterile environments within a brief timeframe. It provides a comprehensive framework for producing, conserving, and applying genetic variety to enhance plant development. TC methods have been employed for the mass propagation and preservation of plants (Thorpe, 2007). These in vitro techniques have also been extensively utilized to generate additional metabolites. TCs are used for in vitro evaluation of disease-resistant plants. Haploidy technologies and procedures are employed to create haploids and triple haploids of heterozygous plants, which

have substantially influenced the farming industry (Germanà, 2011). These BTs are essential to the breeding programs for numerous agronomically significant crops.

Biofertilizers: The nutritional value of the soil must be preserved for optimal plant growth and to effectively enhance plant defense methods. Microbial BT goods, such as biofertilizers, have improved soil fertility, plant resilience, and crop yield. In recent years, encapsulating biofertilizers and nano-fertilizers has proven to be beneficial (Mohammadabadi et al., 2025).

Biofertilizer

Microbial inoculating agents, or BFs, are preparations containing live algae, fungi, and bacteria, individually or in consortia, to enhance plant development and augment agricultural output (Vessey, 2003). BFs comprise advantageous MOs that improve the soil's chemical and biological properties through nitrogen fixation, cellulolytic action, or phosphate solubilization. When used on seeds, plant leaves, roots, or soil, they colonize the rhizosphere through their biological functions, augment nutrient accessibility, stimulate plant development, and boost soil microbiota (Bashan et al., 2014). They are measures that effectively enhance fertility in the soil. Rhizobium forms symbiotic relationships with legume roots, including rhizobacteria, which inhabit the root surfaces or rhizosphere of the soil (Glick, 2012). Wide-ranging BFs, including Blue-Green Algae (BGA), Rhizobium, and Azolla, with crop-specific substances like Azospirillum, Azotobacter, Phosphate Solubilizing Bacterium (PSB), Vesicular-Arbuscular Microbes (VAM), and Anabaena, which are nitrogen-fixing microalgae. These MOs are called biofertilizers and PGPR. The enzymatic activity of PGPR facilitates competition processes and antagonistic actions for the growth of crops, including the suppression of nutrients and phyto parasites; it aids plants in resisting stress from heavy metal contaminants and pollutants (Lugtenberg & Kamilova, 2009). BFs are environmentally sustainable, economically viable, and are manufactured in large quantities on-site if required (Malusá & Vassilev, 2014). The crop output increases by 12-45%, with up to 55% of nitrogen fixed. The sustained application of BFs to the soil over 2-5 years can preserve fertility, owing to the efficacy of parental inoculations, which can successfully sustain plant development and proliferation. They enhance soil texture, pH, and several other characteristics. BFs are sustainable sources of nutrients for plants that supplement BFs at a bit of expense. Compared to synthetic fertilizers, BFs are renewable. They are derived from renewable energy sources (RES), mitigate damage, contribute to developing healthy ground, and, to some degree, assist in removing residual synthetic fertilizers from crops (Adesemoye et al., 2009). Using BF as a contemporary agricultural tool is essential for effectively managing nutrients, minimizing harmful chemical consumption, cost efficiency, and providing clean power for plants in environmentally friendly farming (Figure. 2).

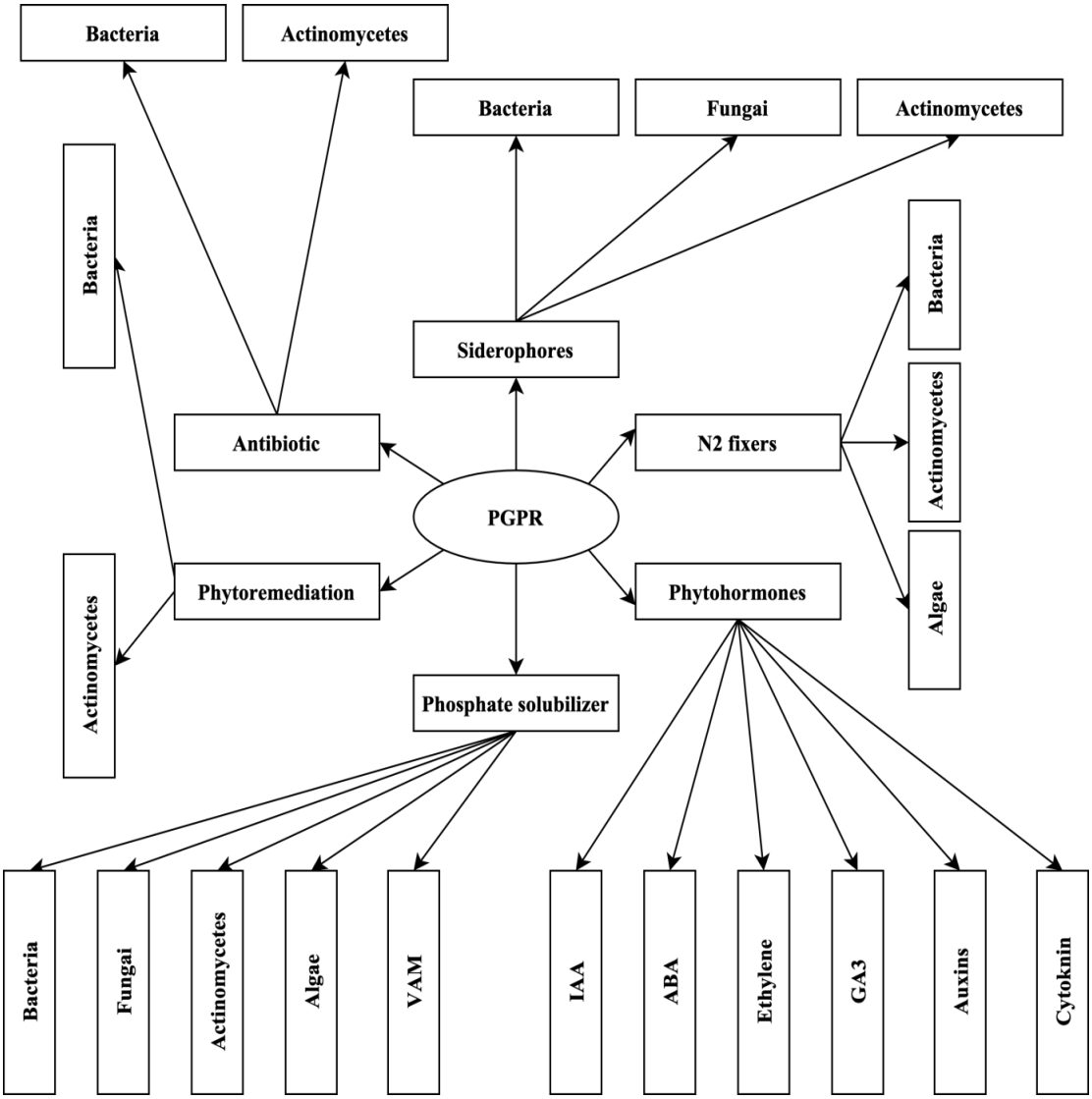

Figure 2. Roles and microbial groups associated with plant growth-promoting rhizobacteria (pgpr) and their mechanisms of action

Biofertilizer carrier: The carrier is a crucial category of inoculants that facilitates the delivery of the optimal quantity of PGPM in an enhanced physiological condition. Diverse materials serve as inoculant carriers to improve the biological efficacy, resilience, and bacterial protection against abiotic and biotic stressors. The components of the material itself are organic, inorganic, or synthesized. A suitable carrier is selected based on availability, cost-effectiveness, ease of use, packageability, and mixability. Moreover, the airline must facilitate gas exchange, particularly for oxygen, requiring excellent water retention capacity and elevated organic matter contents. The physical composition of BFs is defined by the carrier employed. The amalgamation of soil carrier nutrients is used as dry inoculations, including coal ceramics, peat moss inert

substances (bentonite, perlite, kaolin, which silicon dioxide, and vermiculite), organic constituents (sawdust, grain bran, soy flour, and fertilizers), or organic matter (eruption pumice, diatomite this planet, and lapillus) (Herrmann & Lesueur, 2013). Diverse liquid inoculants serve as transporters, including organic oils, oil-in-water emulsions, yeast cultures, and substances. The carrying material used for bacterial inoculations and plants has to be non-toxic. The study delineated the characteristics of the carrier as immediate, abundant, and locally evaluable at a reduced expense, readily sterilizable, and neutral with an easily modifiable pH. The final selection of carriers includes storage viability, microbial proliferation, compatibility with planting gear, cost-effectiveness, and the overarching culture strategy (Allouzi et al., 2022). The study documented those combinations of Farmyard Manure (FYM), including FYM + carbon and earth, FYM + earth, and FYM + charcoal + earth, yield elevated viable numbers of *Azospirillum* (AZ) and sustain viability for up to 30 months. Inoculations were produced using carriers like vermiculite ceramics, FYM waste, coconut shells in powdered form, teak leaf powder, and compost. Locally available materials, including coffee waste, earth, lignite, and burning charcoal, over alternative carriers such as peatland for AZ, exhibiting a survival duration of 250 days and a significantly lower decrease rate in the AZ colony in pressed (Sahu & Brahmaprakash, 2016). Combining black ash and husks, press mud, husk powder, black ashes, and barley husk was effective and acceptable transporters for Rhizobium, equivalent to peat and coal.

Microbial inoculation agents: Classifications, mechanisms, and modes of action

Plant Growth-Promoting Bacterium (PGPB) can enhance plant growth and agricultural production through many mechanisms and is environmentally friendly. These BT microbes inhabit the rhizoplane of root systems and nourish the plants, improving their growth through this mutualistic relationship (Kloepper et al., 1980). The many attributes of PGPB facilitate their active colonization of the roots and mitigate the detrimental effects of plant diseases. The adverse effects of PGPB on plants frequently arise from the production of secondary compounds such as siderophores, antimicrobial agents, cyanide from hydrogen, and hydrolytic enzymes, among others. Chitinolytic action has been shown in several PGPBs (Compant et al., 2005). Chitinolytic microbes are essential in the biological control of fungal infections due to their capacity to lyse chitin, a necessary part of the cell walls of fungi. Siderophores are low-concentration molecules synthesized by various microbes that chelate or sequester ferrous and other elements in the soil. They are essential in the plant extraction of toxic substances due to their ability to complex ferrous ions and render them accessible. Siderophores encompass many chemical components and have several uses, including plant growth stimulation, functioning as biological sensors, biocontrol substances, and bioremediation chemicals. PGPBs impact plant development by producing

auxins. The primary emphasis in contemporary agricultural practices is the application of safe and eco-friendly techniques through beneficial bacteria. These advantageous MOs comprise a variety of natural bacteria that enhance nutrient absorption, improve soil physicochemical qualities, increase soil microbial biodiversity, and promote soil nutrition, crop development, and production. Microbial inoculations are living microbes that function as biocontrol substances and biological fertilizers, yielding several advantageous effects in agriculture. Microbial inoculations are eco-friendly and contain bacteria, fungi, or algae. The beneficial MOs include bacteria and fungi that enhance plant development, nitrogen-fixing algae, stress-tolerant fungi, and pathogen-inhibiting microbes that can perform biological degradation. Microbial inoculations are categorized into four groups based on what they do. They encompass compounds that facilitate plant development advancement, soil clean up, increase of plant resistance, and regulation of Greenhouse Gas (GHG) emissions (dos Reis et al., 2023) (Figure. 3).

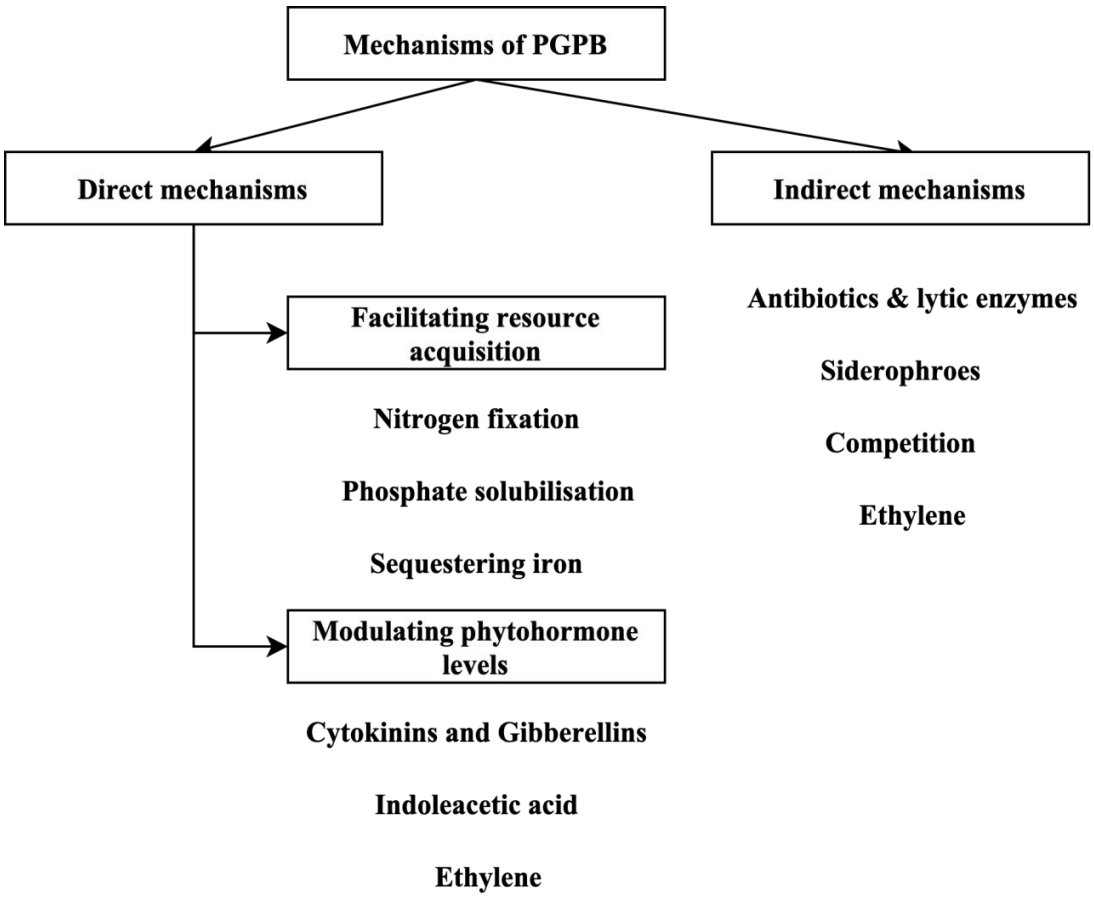

Figure 3. Categorization of mechanisms empl oyed by plant growth-promoting bacteria (pgpb) to enhance plant development

Advantages, limitations, and future scope of biopesticides

Advantages: Biopesticides exhibit their inhibitory impact through several mechanisms, including growth regulation, gastrointestinal disruption, metabolic poisoning, neuromuscular toxicity, and nonspecific multi-site inhibition. These several modalities of action against particular pests eliminate the likelihood of resistance formation, which is prevalent with synthetic pesticides. The extensive application of conventional chemicals in large-scale agriculture over an extended duration, particularly during the Green Revolution, has resulted in issues such as pesticide-induced contamination, post-harvest biological accumulation via metabolism, biodiversity decline, and the emergence of secondary pests alongside the eradication of natural predators and beneficial organisms (Popp et al., 2013). These adverse effects are not linked to the application of BPs. Stringent regulations are consistently enacted on synthetic pesticides to diminish their prevalence over time. For example, the number of active chemicals in traditional pesticides decreased to 260 in 2015 from over 1500 in 2020, while introducing new traditional pesticides into the marketplace declined from 75 in 2010 to 29 in 2015. The diminishing availability of conventional pesticides has led to a heightened demand for BPs due to several advantageous factors. The advantages encompass but are not limited to modifying resistance to pests, exhibiting low toxicity, serving as a supplementary resource to synthetic pesticides, being environmentally friendly, demonstrating specificity (thereby minimizing adverse effects on non-target species and people), being biodegradable and presenting minimal issues with post-harvest pollution, stability toward abiotic stresses, as well as integration within IPM (Glare et al., 2012).

Limitations: If their abilities are adequately harnessed, BPs will supplant chemical pesticides in a few years without markedly impacting production and yield. The BT obstacles to the comprehensive adoption of BPs include the elevated costs of refined commercial goods, the failure to satisfy international demand, varying standard manufacturing processes and guidelines, challenges in determining active ingredient dosages, susceptibility to numerous environmental variables, unstable stability, and delayed efficacy. Anticipating that these limits would be resolved through study advancements in the forthcoming years, farmers, particularly in rural regions, might utilize a crude extract of plants to safeguard crops and enhance production (Marrone, 2014). The efficacy of applying pesticides, including BPs, is optimized when integrated into IPM. An IPM is a pest-control strategy that employs a comprehensive approach, incorporating cultural habits and other appropriate treatment methods into a singular management strategy to achieve a sustainable decrease in pest populations and related issues. BPs confer beneficial effects, including societal acceptance, financial sustainability, and environmental responsibility, with substantial reductions in insect populations, aligning with the three-domain idea of sustainable growth (Chandler et al., 2011).

Prospective outlooks: Microbial inoculations benefit agriculture, finance, studies, and technology by promoting seed efficiency through improved microbial survival rate and increasing crop yield (Bhattacharyya & Jha, 2012). These beneficial MOs exert less detrimental impacts on the natural world than conventional chemical treatments (chemical fertilizers), rendering them a viable agronomic technique and a method for reducing production costs. A primary drawback of inoculants containing microbes is their creation and marketing. Growth necessitates the separation of MOs, examining them for specific traits, and evaluating these organisms through experiments and small-scale assessments, laboratory testing, and standards of microbial inoculations. Future studies should prioritize separating, growing, and measuring beneficial MOs and their effects on ecological and soil health (Malusá et al., 2012). The process of action associated with BT bioremediation might be examined. The alterations in soil biology continue to represent a significant gap that requires more documentation. While the manufacturing methods for ecologically resilient microbe inoculants suitable for integration into IPM systems necessitate minimal expenditure on capital, they are labor-intensive and demand prolonged incubation durations. Pure cultures of MOs and BT microbial groups should be investigated as inoculations, and it is an urgent necessity to enhance their compositions to ensure longevity in agricultural systems. There has been constant advancement in developing increasingly reliable and precisely specified microbiological inoculant solutions. Currently developed bacteria inoculant goods available economically include full details regarding the strain of microbe or consortium of strains, their mechanism of action, duration of storage, and application procedures for illnesses in crops, as well as assessed field effectiveness. While several products on the marketplace apply to various crop kinds, their effectiveness is not significantly substantiated. Systematic endeavors must be directed toward producing microbial consortium inoculants since they will integrate the particular attributes of the included multispecies. The primary consideration is that the inoculant animals must exhibit BT biocompatibility (Mohammadabadi et al., 2024b). These polymicrobial inoculation agents, including diverse MOs with several functions, might be utilized on distinct crops throughout many global areas. Advancements in these multimicrobial goods are pivotal to attaining business success. Using bacteria as inoculants by treating the seeds is a standard procedure, particularly in legumes containing rhizobia. Seed injection offers the benefit of positioning MOs in proximity to the developing roots, thus enhancing their colonization and establishment at the plant-soil interfaces despite the inherent limitations of this process. Numerous methodologies exist for producing BFs, BPs, and other PGPRs, including seed covering, biopriming, and encapsulating procedures. Despite the considerable success of these strategies, further study is necessary to enhance the quality of BT biological inoculations (Bashan

& De-Bashan, 2010). Investigating several potential methods for creating and applying medically validated inoculants containing microbes with enhanced efficacy is essential.

Conclusion

Microbial inoculant-based BFs appeal because they can fix nitrogen, phosphorus, sulfate, sodium, and zinc, solubilize minerals, and promote plant development through hormonal behavior, antibiotics, and the decomposition of organic wastes. Plants can utilize reinforcements and phytostimulators to enhance their development without adequate nitrogen levels. They sprang from the soil and demonstrated proficiency in the rhizosphere. Crop growth-promoting exhibits several functions, including fixing nitrogen, plant hormones, dissolution of micro- and macro-minerals, generation of enzymes, and manufacturing fungicide chemicals or antibiotics. Siderophores possess bioremediation capability by detoxifying pollutants, including insecticides and toxic metals, while regulating plant pathogens as BPs, competing with harmful microbes. The extensive and effective use of genetically engineered biotech crops globally has demonstrated the promise of BT in enhancing crop productivity. Nonetheless, the advent of insect immunity to BT-cotton has periodically prompted concerns regarding its low resilience to potential growth in insect resistance. They biologically enhance and sustain the soil and root system through MOs, including bacteria, fungi, and algal cells. This paper examines the concept of single or consortium organisms engaging in various activities, including nitrogen fixation, phosphate dissolution, sulfate dissolution, and zinc dissolution, via enzyme and acid synthesis. The influence of microbes as BFs and the function of BPs promote plant development by increasing insect tolerance and enhancing crop nutritional and health security.

Author contributions

Reddy B contributed to the conceptualization of the study, coordinated the project, and performed the final review of the manuscript. Mohamed Jaffar A was responsible for the literature survey, data collection, and development of the methodological framework. Indumathi S M prepared the initial draft of the manuscript and assisted with figure design and formatting. Stapathy S N contributed to the experimental planning and supported resource acquisition and management. Adarsha Harinaiha participated in critical manuscript editing, reference verification, and formatting. Ramakant conducted data analysis, created visualizations, and supported the interpretation of results. Prerak Sudan provided technical supervision, reviewed the manuscript for accuracy, and ensured logical flow and structural coherence.

Data availability statement

The data that support the findings of this study are currently not publicly available as the manuscript is under review and the study has not yet been published. However, the data may be made available from the corresponding author upon reasonable request.

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Ethical considerations

This research did not involve human participants, animal testing, or the use of sensitive personal data. Therefore, ethical approval was not required. All methods and procedures used in this study comply with institutional, national, and international guidelines and regulations applicable to the field of research. The authors affirm that there are no ethical conflicts or issues associated with this work.

Funding

This study is based solely on a review of existing literature and does not involve any experiments on humans, animals, or genetically modified organisms conducted by the authors. As such, ethical approval and informed consent were not required. All references, data, and studies have been properly cited by academic and publishing ethics.

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چکیده

هدف: بهره‌وری کشاورزی در حال حاضر با روند نزولی روبرو است که ناشی از کاهش حاصلخیزی خاک و شیوه‌های نادرست کشاورزی است. وابستگی بیشتر به کودهای شیمیایی مصنوعی نه تنها فرسایش خاک را تسریع می‌کند، بلکه مشکلات شدید زیست‌محیطی و سلامت انسانی را نیز افزایش می‌دهد. هدف این مطالعه بهبود عملکرد محصول، بازسازی سلامت خاک و ترویج

شیوه‌های کشاورزی زیست‌محیطی است، به ویژه بیوفرتیلایزرها (BF) و بیوپستی‌سایدها .(BP) هدف این پژوهش بررسی کارایی آن‌ها برای افزایش ظرفیت اینوکولانت‌های باکتریایی به عنوان بیوفرتیلایزرها و کارایی آن‌ها در بهبود عملکرد محصول است.

مواد و روش‌ها: یک مطالعه تجربی مبتنی بر مزرعه برای ارزیابی تأثیر اینوکولانت‌های باکتریایی بر حاصلخیزی خاک و عملکرد محصول انجام شد. بیوفرتیلایزرهای انتخاب‌شده شامل سویه‌های باکتریایی تثبیت‌کننده نیتروژن و حل‌کننده فسفات بودند. این‌ها در پلات‌هایی که محصولات رایج کشت می‌شوند، تحت سطوح مختلف ورودی‌های ارگانیک و غیرارگانیک آزمایش شدند. پلات کنترل از کودهای شیمیایی سنتی استفاده کرد. پارامترهایی مانند شرایط تغذیه‌ای خاک، سرعت رشد، عملکرد و مقاومت به آفات در طول فصل نظارت شد. نمونه‌های خاک اولیه و بعدی برای ارزیابی تغییرات در محتوای تغذیه‌ای و فعالیت میکروبی تجزیه و تحلیل شدند. تحلیل آماری داده‌ها برای مقایسه اثرات درمان انجام شد.

نتایج: نتایج بهبود قابل توجهی در عملکرد محصول و حاصلخیزی خاک در پلات‌های درمان‌شده با بیوفرتیلایزرها نسبت به پلات‌های تنها درمان‌شده با کودهای شیمیایی نشان می‌دهد. کاربرد اینوکولانت‌های باکتریایی مواد مغذی را افزایش داد، تولید بیوماس را بهبود بخشید و تنوع میکروبی خاک را افزایش داد. علاوه بر این، استفاده از بیوفرتیلایزرها وابستگی به ورودی‌های مصنوعی را کاهش داد و به شیوه‌های کشاورزی پایدارتر و دوستدار محیط زیست کمک کرد. وقوع آفات در پلات‌های منتسب به بیوفرتیلایزرها نیز پایین بود، که نشان‌دهنده اثر ترکیبی با بیوپستی‌سایدها است.

نتیجه‌گیری: این مطالعه نقش امیدوارکننده بیوفرتیلایزرها و بیوپستی‌سایدها را در کشاورزی پایدار تأکید می‌کند. کاربرد آن‌ها نه تنها محصول و خاک را بهبود می‌بخشد، بلکه تأثیر زیست‌محیطی و هزینه‌های تولید را کاهش می‌دهد. بیوتکنولوژی، به ویژه به عنوان اینوکولانت‌های میکروبی، پتانسیل عظیمی برای حمایت از امنیت غذایی جهانی دارد. با این حال، برای بهره‌برداری کامل از مزایا، قوانین گسترده بیوامنیتی و سیستم‌های آموزشی و حمایتی کشاورزان باید اجرا شود. ادغام راه‌حل‌های مبتنی بر بیولوژی در کشاورزی می‌تواند مسیر لازم برای پایداری بلندمدت کشاورزی در سیستم‌های کشاورزی با ورودی کم را فراهم کند.

کلمات کلیدی: بیوپستی‌سایدها، آفت‌کش‌های شیمیایی، گروه‌های میکروبی، مدیریت آفات، کشاورزی پایدار

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