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Role of Microbes in Biotechnology and Sustainable Agriculture

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Abstract

Microbial biotechnology plays a crucial role in sustainable agriculture by harnessing beneficial microorganisms for various agricultural applications. This review explores the diverse roles of microbes in agriculture, focusing on their use as biofertilizers and biopesticides. Key microbial groups such as Plant Growth-Promoting Rhizobacteria (PGPR) and fungal biocontrol agents are highlighted for their contributions to enhancing crop nutrition, combating pests and diseases, and promoting environmental sustainability. The interaction dynamics within the plant microbiome, including the rhizosphere and endosphere, are also discussed, emphasizing their impact on plant health and productivity under changing climatic conditions.

Keywords: Biopesticides; Biofertilizers; Rhizobacteria; Endosphere

Introduction

A rapidly expanding area of biological sciences called biotechnology has several uses in sustainable agriculture. In biological sciences, it entails employing genetic engineering to change living things or their components to produce useful products for various uses. The world's expanding population will significantly strain food production and agriculture by the end of 2033. In order to meet the rising demand for food, this offers a difficulty. A rapidly expanding area of biological sciences called biotechnology has several uses in sustainable agriculture. In biological sciences, it entails employing genetic engineering to change living things or their components to produce useful products for various uses. In order to meet the rising demand for food, this offers a difficulty. Experts like Mostafiz, Rahman & Rahman [1] and Barea [2] predict that by 2050, the demand for agricultural products will have increased by at least 70%.[1] As more people become aware of the significance of food security, this understanding of the necessity for sustainable agriculture techniques will grow increasingly pronounced. Microbial biotechnology is essential for developing agricultural science in a number of areas, including nutrition, food security, and food safety. The basis for biotechnology research, technology development, and the production of new goods is genetic material derived from plants, animals, and microbes. By locating, isolating, cloning, and transferring desirable genes between species, biotechnology technologies have transformed breeding and rendered outdated the classic Mendelian population conceptions. Identifying genetic variants, comprehending how genes work, and improving transgenic organisms with particular advantageous features are the ultimate goals of biotechnology [3]. Globally, agricultural methods are used to achieve sustainable economic and environmental growth while protecting the environment. The junction of the economy and the environment (agroecology), environmental consciousness, and living standards are key components of the idea of "sustainable development." Developing effective strategies to reduce the negative consequences of environmental change, manage pests and illnesses, and recycle nutrients for sustainability, stressors are essential. For ecological and economic sustainability, controlling the microbiome of plant roots is crucial [2]. Agriculture biotechnology, general microbiology, and microbial ecology are all connected by agricultural microbiology. In both natural and agricultural ecosystems, it focuses on comprehending how microorganisms are distributed across plants, animals, and soil conditions [4]. Recombinant DNA technology is used to artificially insert genes into the genetic makeup of transgenic plants. These genes may originate from unrelated creatures like bacteria or animals as well as from members of the same or other species [5].Various advantages of genetically modified crops include delayed ripening for longer shelf life, resistance to pests and diseases to use fewer pesticides, resistance to fungi and viruses, and tolerance to herbicides for better weed control [6,7]. By minimizing dependency on agrochemicals, notably pesticides, microbial biotechnology supports sustainable agriculture. It does this by introducing genes into attractive plant kinds that offer tolerance or resistance to biotic and abiotic stressors. Improved pest and disease resistance, increased resiliency to environmental pressures, bioremediation of dirty soils, higher production, and better nutrient uptake are only a few effects of biotechnology on sustainable agriculture. The employment of environmentally benign symbiotic microorganisms in place of hazardous fertilizers and pesticides is one promising method for sustainable agriculture. These bacteria have the ability to improve crop nutrition, defend against viruses and pests, and lessen the consequences of pollution and climate change. Natural resource management, environmental concerns, and public policy difficulties are just a few of the many facets that make up agriculture. It uses a variety of techniques [8].

Potential Significance of Beneficial Microbes in Sustainable Agriculture

In the approaching decades, utilizing the advantageous microorganisms in sustainable crop production will become a key priority. The most biodiverse ecosystem on Earth is thought to exist in the soil matrix, which serves as a main repository for microorganisms that interact with plants. This environment's critical processes, which especially affect plant health, are controlled by the soil microbiome. The ability of the microbiome to give nutrients (phosphorus solubilization and nitrogen fixation), enhance nutrient uptake from the soil, and promote plant protection are just a few of the roles that have been attributed to it in tight relationships with plants [9]. The natural soil microflora, which contains a variety of beneficial bacteria and fungi, including the arbuscular mycorrhizal fungus known as plant-growth-promoting rhizobacteria (PGPR), is what organic farming depends on the most [10,11]. The ability of beneficial microbes to digest phosphorus for their own needs which is therefore available in sufficient amounts as its soluble form in soil is one of their main advantages [12]. It has been documented that the solubilization process is actively carried out by the bacteria Bacillus, Pseudomonas, Micrococcus, Flavobacterium, Fusarium, Sclerotium, Aspergillus, and Penicillium [13]. The main factors limiting the productivity of the crops are biotic and abiotic stressors [14]. For the purpose of improving crops under stress, many modern scientific technologies have been broadly linked, and the role of PGPRs as bioprotectants has emerged as being of particular significance in this regard [15].

Plant Microbe Interactions

Microorganisms, for example, can help and control nutrient availability and acquisition and promote stress tolerance, which can have an impact on agricultural output. The plant microbiome's species variety and microbial community richness, as well as the variables influencing it and its functioning, remain mostly unknown. The significance of this topic is Microbiome of the rhizosphere and sustainable agriculture. In recent years, there have been an increasing number of scholarly articles on this subject, as shown by studies concentrating on unique plant niches and how they modify their specific microbial populations. Understanding the key factors that influence the composition of the plant microbiome, which is a dynamic and adaptable part of the host, is crucial to changes in environmental (biotic and abiotic) conditions. Recent research has focused on different components of the plant microbiome independently in order to comprehend the variables that affect its assembly and the dynamics from a phylogenetic and functional perspective. The so-called rhizosphere, endosphere, and phyllosphere are three significant compartments where microbial cells can establish and grow [16]. Various significant crop species and their natural relatives have not yet been investigated for their associated bacterial communities, despite the fact that the plant microbiome is thought to be a vast treasure trove of microbial variety. Outbreaks have been documented to better comprehend the importance of the plant-associated microbiome in the protection of pathogens [17,18]. The development of a thorough understanding of the mechanisms underpinning plant-microbe interactions in the rhizosphere has been hampered by the absence of an adequate technique. The main difficulties stem from the requirement to profile an amazing group of processes where the diverse and large microbial communities are mostly made up of uncultivable microorganisms [19]. These molecular-based methodologies are crucial for determining how stresses caused by biotic and abiotic stress factors affect soil microbiome diversity and plant-microbe interactions in the context of current climate change. A greater knowledge of the interactions between plants and their microbiomes would enable soil bacteria to better relieve agricultural stress. Numerous stressors, such as salt, drought, nutrient deficiency, pollution, diseases, and pests, among others, can change how plants and microbes interact in the rhizosphere [20]. Researchers found that the structure of plant roots in soil can be affected by the presence of even little amounts of water. This discovery creates new opportunities for improving water and nutrient aging for significant food crops. The extent of root branching affects how effectively crops absorb water and absorb nutrients. Therefore, it is crucial to comprehend how root branching is regulated [21].

Microbial Interactions across Plant, Soil, and Environmental Interfaces

The majority of the other species that are connected to plants are bacteria. These include the rhizosphere, soil microorganisms connected to subterranean plants, endophytes within plants, and epiphytes on plant surfaces. Organs and soil interfaces for sustainable agriculture using biotechnology. Agriculture places a special emphasis on the symbiosis between legume plants and soil-dwelling rhizobia, and more study has focused on characterizing the molecular processes that produce species-specific cooperation [22]. Host-specific flavonoids that are secreted in the root exudates influence interactions between legumes and rhizobia. Numerous rhizosphere bacteria have the ability to activate plant defense mechanisms by triggering a systemic response in plants. Induced systemic resistance, or ISR, is the term used to describe signaling pathways that result in increased host pathogen resistance after exposure to nonpathogenic root zone microorganisms [23,24].

ISR has been demonstrated to be induced by a number of bacteria, including Bacillus species, which have been utilized to examine advantageous effects under abiotic stress settings. Bacterial endophytes, which are used to improve plant agronomic characteristics and biologically control a variety of plant diseases, may be of particular interest because they have the benefit of being relatively protected from the competitive soil environment. In addition, they frequently grow in the same plant tissue where bacterial plant pathogens are discovered.

Types of Root-Associated Microorganisms

The saprophytic or symbiotic relationships between the plant and the prokaryotic bacteria and eukaryotic fungi have the potential to be harmful or advantageous depending on their trophic/living behaviors. A small subset of these microorganisms, referred to as "endophytes," is able to penetrate and reside within plant tissues, while the great majority of them remain in the rhizospheric soil or rhizoplane [25]. It is acknowledged that soil bacteria are an important part of the many interrelated elements that contribute to the environmental quality needed for a sustained, healthy food supply. The rhizodeposition pools are what draw microbes to and keep them in rhizosphere microhabitats [16]. There are many different types of organisms in the soil microbiome, but studies on the soil microbiome have focused primarily on bacteria, fungus, and archaea.

Beneficial Rhizosphere Microorganisms

PGPR, antagonists of plant diseases, or decomposers of organic matter (detritus), beneficial saprophytic rhizosphere bacteria improve plant performance [26]. The biological control of plant diseases and nitrogen cycling are just a couple of the important ecosystem processes that the PGPR are known to take part in [27], N2-fixing bacteria and multipurpose arbuscular mycorrhizal (AM) fungi are examples of beneficial plant mutualistic symbionts [28]. Rhizobia, a collective word for bacteria from several genera, are able to fix N2 in mutualistic symbiosis with legume plants [29]. Nitrogen-fixing microorganisms turn atmospheric nitrogen to ammonia, which is then changed into forms that plants may use (ammonia and nitrate) [30] (Figures 1-2). A vast group of frequently unidentified or ill-defined microorganisms that interact well with plants and in soils are known as agriculturally relevant microfloras [31].

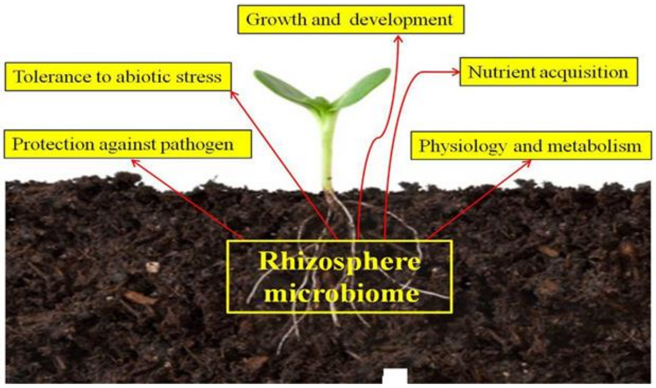

Figure 1: *Rhizospheric soil.*

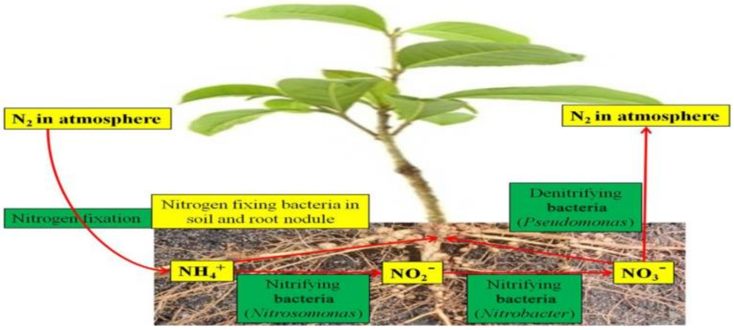

Figure 2: *Nitrogen-fixing microorganisms*

Plant-Growth-Promoting Rhizobacteria

The transformation, mobilization, solubilization, and other processes that take place with regard to nutrients from a finite nutrient pool and, consequently, the uptake of crucial nutrients by plants to realize their full genetic potential [32]. The use of PGPR has been identified as having a possible function in creating sustainable frameworks for crop production. The PGPR are distinguished by some inherent uniqueness, such as the ability to colonize the surface of the root or superficial intercellular spaces of the host plant; they must promote plant growth; they must survive, multiply, and compete with native microbiota in rhizosphere microhabitats at least for the time needed to express their beneficial plant growth promotion activities; and they must promote plant growth [33]. Additionally, PGPR contributes to the solubilization of other nutrients and mineral phosphates, increases stress tolerance, and enhances soil structure and organic matter content [34]. More soil-organic nitrogen is fixed by rhizospheric microorganisms in PGPR [35]. Therefore, they help in reducing the need for nitrogen and phosphate fertilizer and promote release of the nutrients. 192 Biotechnology for Sustainable Agriculture nitrogen, and other nutrients in the plant soil system [36].

Function of PGPR

1. Protection of the environment and natural resources [37].
2. The solubilization of phosphorus
3. Manufacturing of growth regulators for plants
4. Mobilization of potash [38]
5. Microbes as biopesticides and fertilizers [39]
6. Manufacturing of volatile organic compounds [40]
7. Microorganisms as biotic triggers [41]
8. Microbiological reactions to stress in agriculture [42]
9. Microbiological conflict [43].

Mechanism of Action of PGPR in Rhizosphere Region

The entire microbial community in the rhizosphere niche is altered by PGPR-mediated plant growth promotion through the synthesis of different chemicals. Indirectly, PGPR increase plant growth by reducing the negative effects of various pathogens on plant growth and development in the form of biocontrol agents. Directly, PGPR encourage resource acquisition (nitrogen, phosphorus, and essential minerals) or balance plant hormone levels. Associative nitrogen fixation and PGPR's method of action are two common ways that microbes control plant nutrients. Lowering of ethylene levels, synthesis of siderophores, generation of growth regulators, VOCs, solubilization of nutrients, and encouragement of mycorrhizal activity [44]. Microbial Biotechnology and Sustainable Agriculture. To fully implement bacterium-assisted phytoremediation of trace element-contaminated soils, key processes in plant bacteria interactions and colonization by inoculation strains still need to be elucidated.

Table 1: *Categories of Microbial Biopesticides.*

s	Microorganisms	Target Pest	Mode of Action
Bactericide	Agrobacterium radiobacter	Crown gall (Agrobacterium tumefaciens)	Antagonist and antibiosis
	Bacillus polymyxa	Crown gall	Antagonist and antibiosis
	Bacillus sphaericus	Crown gall	Antagonist and antibiosis
	Bacillus subtilis	Bacterial pathogen	Colonizes on plant root and competes
	Pseudomonas fluorescens	Several bacterial diseases such as frost-forming bacteria	Crowds out and controls the growth of plant pathogens
Fungicide	Bacillus subtilis	Soil foliage, fungal pathogens such as Rhizoctonia, Fusarium, Aspergillus, and others	Colonizes on plant root and competes and antibiosis
	Pseudomonas syringae	Postharvest disease	Utilize seed exudates, produce a wide spectrum of bioactive metabolites
	Bacillus pumilus	Seedling disease	Colonizes on plant root and competes and antibiosis
	Streptomyces	Fungi-causing damping off, stem, and crown rots	Mycoparasitic, antagonist, and antibiosis
	Pseudomonas fluorescens	Plant soil-borne diseases, fireblight	Utilize seed and root exudates and colonize, produce a wide spectrum of bioactive metabolites
	Trichoderma viride/ harzianum	Soil-borne fungal disease	Mycoparasitic, antagonist, and antibiosis

	Burkholderia cepacia	Fungal pathogens	Controls fungi via seed treatment
	Gliocladium catenulatum	Seed-borne and soil-borne diseases	Enzymatic mechanism
	Candida oleophila	Postharvest pathogens	Colonization of diseased tissues

Application of High-Quality Microbial Inoculants

A thorough analysis of the formulation and practical views of inoculants technology for PGPR was recently published by Bashan, de-Bashan, Prabhu, and Hernandez [45]. They suggest several major research goals for developing delivery methods for PGPR and rhizobia. The following requirements must be met for the successful application of microbial inoculants in agriculture: (1) strengthen the scientific and technological foundations of inoculum production and application; (2) develop specific normative for each type of inoculant and its application, whether to seeds, soil, or a transplanted plant that has already been microbeized; (3) establish quality-control protocols; (4) reduce the fluctuation of field results; and (5) spread knowledge by outlining benefits and drawbacks for society.

Seed Treatments for Sustainable Agriculture

Agricultural Seed Treatments for Sustainability 90% of food crops are grown from seed, making seed an essential component of sustainable growth in agricultural production. If not promptly dealt with, seed-borne, early-season illnesses and insects have devastating effects. In modern agriculture, the focus is on producing more with less land, water, and labor. In order to combat plant pathogens, traditional environmentally friendly disease management techniques like sanitation, crop rotation, mixed cropping, adjusting the date of sowing, fallowing, summer plowing, green manuring composting, etc. are currently being reevaluated as a part of integrated pest management [46].

Encourage Beneficial Microbe Establishment at Rhizosphere

Gaining a biased rhizosphere undoubtedly creates new prospects for agricultural advancements based on utilizing advantageous microbial services to reduce pesticide inputs and so achieve sustainable environmental and economic goals [47].

1. Using agricultural practices to harness the microbial communities in the rhizosphere.
2. Understanding how plants influence the rhizosphere's microbial community structure.
3. The idea or practice of the "biased rhizosphere".

In order to ascertain whether the rhizosphere may be manipulated (biased) to strengthen beneficial organisms while preventing the presence of diseases, a number of approaches are currently being pursued. Due to the considerable gaps in our understanding, the objective research themes present numerous challenges.

Beneficial Microbes in Agriculture under Changing-Climatic Scenario

One of the main issues facing the world today is climate change, which has an impact on life on Earth. The general shape, functioning, and photosynthesis (the assimilation of carbon) of plant specimens as well as their interactions are typically impacted by climate change [48]. A rise in atmospheric carbon dioxide (CO_2) lowers the nitrogen content of crops, which may delay the onset of many pests and illnesses and alter the makeup of the weed flora that grows alongside the crops [49]. Agriculture suffers a variety of difficulties as a result of the excessive and illegal usage of chemical fertilizers. It is well recognized that a significant portion of the vital, naturally occurring micro- and macronutrients in soil are destroyed by synthetic fertilizers [50]. Changes in plant physiology and root exudation are anticipated to result from changes in environmental conditions brought on by a changing climate. To advance our understanding of native biodiversity and microbial community structure in the context of a changing climate, research is crucial [51].

Biofertilizers

A preparation containing active or dormant cells of effective strains of nitrogen-fixing, phosphate-solubilizing, and cellulytic microorganisms, among others, is referred to as a biofertilizer. Biofertilizers, in contrast to chemical fertilizers, are living microorganisms that aid plants in accessing the nutrient availability in the rhizosphere but do not themselves produce nutrients [52]. Numerous microorganisms, such as nitrogen-fixing soil bacteria (Azotobacter, Rhizobium), nitrogen-fixing cyanobacteria (Anabaena), phosphate-solubilizing bacteria (Pseudomonas sp.), and AM fungus, are frequently utilized as biofertilizers [53]. Similar to this, cellulolytic microorganisms and phytohormone (auxin)-producing bacteria are also utilized in the creation of biofertilizers. These microbial formulations are used to speed up specific microbial processes so that more nutrients are available in plant-assimilatable forms. A cheap and sustainable source of plant nutrients is biofertilizers. These are the types of helpful soil microorganisms that have been cultivated and packaged in the lab in acceptable carriers. A material that gives a biofertilizer

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formulation a longer shelf life is known as a carrier. Examples include peat, lignite powder, vermiculite, clay, talc, rice bran, seed, charcoal, soil, rock phosphate pellets, paddy straw compost, wheat bran, and combinations of these materials.

Biopesticides

Using biotechnology to create synthetic insecticide alternatives to combat insect pests is also acceptable [54]. To safeguard the plant throughout the crucial seedling stage, coating formulas for these helpful organisms may be created. Bacterial and fungal agents like Trichoderma spp., Ampelomyces quisqualis (used to combat grape powdery mildew), and Bacillus subtilis (used to control plant diseases) are frequently utilized as second-hand biopesticides [55]. A microorganism with the agile attribute either directly affects the pathogen as a biocontrol agent (such as Contans) or creates a chemical during fermentation that functions as a control (such as Sonata) [56].

The argument for consistent home cooking has made conventional agriculture heavily reliant on pesticides. Growers are investigating new ecologically friendly methods to replace, or at least augment, the current chemical-based processes as a result of the growing clientele and spend on shipboard maintenance. Biopesticides have gainedpopularity as a potential replacement for chemical pesticides. The efficacy of biopesticide bacteria such as Bacillus circulans, Agrobacterium radiobacter, Bacillus pumilus, and Pseudomonas aureofaciens and fungi such as Ampelomyces quisqualis, Fusarium oxysporum, Gliocladium virens, Trichoderma harzianum, and Pythium oligandrum was utilized by many countries for their growth in the field of agriculture for sustainable development [57].

Conclusion

Biotechnology is becoming increasingly important in the constantly expanding field of sustainable agriculture. This discipline uses genetic resources from plants, animals, and microbes to create novel solutions for sustaining agricultural output while protecting the environment. Sustainable agriculture methods include a variety of techniques and tactics that address economic and environmental problems while taking into account the complex interplay of social, physical, and biological aspects.

Agriculture has an impact that extends beyond agricultural cultivation to include the management of critical natural resources such as surface and groundwater, forests, recreational areas, and wildlife. Climate change is a major global issue that affects all life on Earth, and sustainable agriculture aims to limit its consequences. Biodiversity, the foundation of all agricultural plants and animals, is crucial to agricultural success. Agro ecology, which uses natural biodiversity to increase crop productivity, is a popular technique. This is accomplished by cultivating beginning crops, which improves the environmental conditions for later crops. In essence, sustainable agriculture attempts to integrate agricultural practices with ecological and economic sustainability, addressing pressing global concerns while guaranteeing the well-being of both people and the environment. It is driven by biotechnology and a thorough understanding of genetic resources.

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