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Role of soil microbial sources for productivity uplifting and stress mitigation in crop plants

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Abstract
The growing global population and decreasing resource constraints pose a daunting challenge for sustainable food production and plant stress reduction, particularly in developing countries. The soil microbiome is crucial to the functioning and resilience of agricultural ecosystems, helping with activities including organic matter decomposition, nitrogen cycling, and plant growth promotion. However, the soil microbiome is continually challenged by different environmental challenges, including drought, heavy metal contamination, salt, and climate change, which can drastically disturb the fragile equilibrium of the soil ecosystem. To improve plant growth and minimise negative environmental impacts, these microbes use a number of direct and indirect processes, such as phytohormone regulation, nutrient solubilisation, stress-alleviating enzyme production and antimicrobial chemical creation. Integrating microbial solutions into agricultural systems is an eco-friendly technique for revitalising soils, increasing crop yields and ensuring agricultural sustainability amid environmental difficulties. The current review highlighted the present understanding of various soil microbial sources and their roles in productivity and stress mitigation in crop plants.

Keywords: Soil microbiome, plant stress, organic matter, phytohormone, eco-friendly technique

Introduction

Population growth is driving the rise in worldwide demand for agricultural products, which has resulted in greater production rates, topsoil degradation, lower organic matter levels, and impaired soil ecological services (Etesami *et al*., 2023) [17]. These changes have been heavily influenced by food demand and supply ratios, whereas a growing global population need a significant increase in agricultural production to meet current demand (Tilman *et al*., 2011) [42]. However, conventional agriculture is seeing a decline in output and an increase in input costs. Furthermore, natural and anthropogenic activity reduces vegetable productivity, resulting in land degradation and lower crop yields.

Land use patterns often alter as a result of modernisation and urbanisation, reducing arable land availability. Farmers are also abandoning this approach due to the low-cost advantages and the introduction of new seed varieties and technologies. Some underutilised vegetable crops have good nutritional status and need to protect the varieties from adverse climatic conditions (Harini *et al*., 2025; Sundarrajan *et al*., 2024; Vaishnavi *et al*., 2023) [20, 41, 43]. Agriculture supports more than half of India's population. Furthermore, the heavy use of chemical fertilisers and pesticides to increase crop output is harmful to soil and food quality (Kang *et al*., 2016) [23]. Plants are subject to a variety of abiotic and biotic changes. As the world's population grows, agrarian countries such as India will face increased demand for agricultural supplies. In order to meet population demands, farmers utilise organic fertilisers, inorganic chemicals and pesticides to increase production. However, these chemicals and pesticides harm soil fertility (Rammohan *et al*., 2023; Singh, 2015) [32, 39]. The primary problem in agricultural science is to create a technique for increasing crop output sustainably. Because of the significant detrimental repercussions of inorganic fertilisers and pesticides, many academics have recently concentrated their efforts on discovering strategies to mitigate these effects. Soil microbes play an important role in agricultural ecosystems by decomposing soil organic matter, preserving soil fertility, promoting nutrient cycling for plants, and boosting overall production.

They are required for the transformation and transport of nutrients from the soil to the plants. The structure and composition of soil microbial communities are frequently utilised as indicators of soil quality. The soil microbiome is constantly challenged by numerous environmental pressures, which can drastically affect its composition, diversity and general functionality (Chu, 2018; Abdul Rahman *et al*., 2021) [8, 1].

Several microbes have been known to play a role in plant growth promotion in a variety of ways, such as through biocontrol action, i.e., the suppression of plant pathogens and the production of certain substances that stimulate plant growth; through their role in bioremediation, i.e., the cleanup of pollutants; or through their stress tolerance capabilities, which may help plants dodge different types of stress. This involves controlling phytohormone signalling, avoiding plant infections, and improving nutrient availability and uptake by plants (Majhi *et al*., 2023) [28]. Plant growth-promoting rhizobacteria (PGPR) and their significance in increasing yields of vegetables are still being investigated in a number of methods. The rhizosphere is a zone of high biological activity surrounding a plant's root surfaces. PGPR, a naturally occurring soil bacterium, aggressively colonises plant roots and helps the plant. PGPR contribute to a multitude of beneficial processes in soil, including crop residue decomposition, soil organic matter synthesis, soil organic matter mineralisation, and mineral nutrient immobilisation, all of which promote soil fertility. More research is needed to better understand soil PGPR communities and their roles in vegetable production. Many PGPR taxa have been linked to solanaceous vegetable crops, including *Pseudomonas*, *Azospirillum*, *Klebsiella*, *Alcaligenes*, *Azotobacter*, *Enterobacter*, and *Serratia*, as well as *Pseudomonas* and *Bacillus*. This review highlights an overview of the beneficial effects of microbes for enhancing sustainable vegetable production and overcoming biotic and abiotic stresses.

Significance of soil microbes

With over 17% of all biomass, microorganisms constitute the most abundant living things on Earth (Bar-On *et al*., 2018) [2]. The most intricate ecosystem is found in soil, which is thought to include 4-5×1030 microbial cells. Soil organisms like bacteria, viruses, and spores make up the majority of the soil microbiome (Dubey *et al*., 2019) [12]. Due to their contribution to overall ecosystem function and services, these microscopic organisms are essential parts of terrestrial habitats (Vincze *et al*., 2024) [44]. An essential site for interactions between soil and vegetation microbial communities is the rhizosphere, which envelops plant roots. It functions as an ecosystem hotspot where complex interactions between bacteria, plants, and other organisms take place. According to Massalha *et al*. (2017) [29], organic compounds released by plant roots support and promote the activity of bacteria in the rhizosphere. The leading bacterial groups in the rhizosphere soil are Proteobacteria and Acidobacteria, and both are crucial to the cycles of nutrients and carbon (Islam *et al*., 2020) [22]. They break down intolerant organic detritus, improve nitrogen fixation (N2), diminish plant illnesses, improve crop growth, and produce useful compounds like auxins and antibiotics (Bhatti *et al*., 2017; Ebrahimi-Zarandi *et al*., 2023) [5, 14].

Plant-derived hormones, including auxin, gibberellin and cytokinin, which control plant growth and decrease plant ethylene levels to lessen stress, can also be produced by rhizosphere and endophytic bacteria. A kind of PGPR known as nitrogen-fixing diazotrophs supplies 30-50% of the total ammonia in agricultural areas, making them a significant source of nitrogen in soil (Smercina *et al*., 2019) [40]. These bacteria are essential to plant health because they encourage growth and the intake of resources. These bacteria serve as vital for ecologically sound agriculture because they can increase plants' resistance to both abiotic and biotic stresses.

By boosting nutrient intake, mycorrhizal linkages also aid in alleviating stress. In nutrient-deficient or stress-prone substrates, VAM improve both phosphorus and micronutrient accessibility and increase root surface coverage for the intake of nutrients (Ebbisa *et al*., 2022) [13]. Arsenic and arsenate-tolerant microbe consortia significantly enhanced the growth of rice and detoxification in field testing, boosting biomass in the root system and shoots and reducing arsenic buildup in edible parts.

Effect of biotic factors on productivity and quality of vegetables

According to Reddy *et al*. (2022a) [34, 36], vegetables are a significant source of vitamins, minerals, and other substances that may help compensate for micronutrient deficiencies. Over the past 25 years, vegetable production has increased, and the value of the overall vegetable trade now surpasses that of the grain trade. Eastern Asia's temperate or subtropical zones yield the largest harvests. Low yields are caused by biotic variables, high temperatures, and insufficient soil moisture because vegetables are susceptible to environmental extremes (Reddy *et al*., 2022b; Reddy *et al*., 2023) [34, 36, 35]. These worries will be made worse by climate change. Vegetable expansion is unprofitable due to crop failure, which is prevalent across changing climates. Yields are low, quality declines, and diseases and pests rise. Lastly, this raises concerns about the nutrients that are available in the human diet. Due to water constraints brought on by the monsoon failure, crop yields in significant drought-prone areas are below average. Pollination of numerous vegetable crops, such as root crops, onions, and cabbage, is impacted by shifts in insect species' range. Weed incursion in farming areas is another challenge.

Climate change can harm food safety and trigger major losses through storage, including shifting the population of fungi that release aflatoxin, in addition to impacting the quality of vegetables after harvest. Additionally, it affects how vegetables are distributed and stored, which could be made worse by extreme weather (Costello *et al*., 2009; Reddy and Dhathri, 2023) [9, 33]. Pathogen-host associations, insect dispersion and ecology, movement patterns, and seasonal capabilities all have an impact on the physical and biochemical alterations brought on by climate change, pests, and diseases. Host vulnerability and host-parasite relationships can be affected by changes in the circumstances surrounding a pathogen and host.

Soil microbes contribute to mechanisms for abiotic resistance

Depending on the richness and variability of living organisms, plants use a variety of stress tolerance strategies in response to abiotic stressors (Elhindi *et al*., 2017) [15]. Sugars, fatty acids, amino acids, and secondary metabolism products are among the nutrients that are commonly abundant in plant root rhizospheres. These substances serve as potent chemical lures for microbes. By consuming plant metabolites and generating essential biological components such as appropriate solutes, antiviral compounds, enzymes, gibberellins, cytokinins, auxins, and ABA, these tiny living things flourish in the rhizosphere.

By causing a variety of metabolites, including phytohormone generation, growth-inducing metabolites, osmoprotectants, heavy metal capture, siderophore induction, morpho-anatomical changes, physiological characteristic modulation through the induction of volatile molecules, and positive nutrient profile modulation, PGPM stimulates crop growth and metabolism (Kazan, 2013) [25]. Particularly, *Jeotgalicoccus huakuii* NBRI 13E showed enhanced growth promotion in salty soils, boosting the biomass of maize roots and shoots and raising its chlorophyll stability index when exposed to salt (Misra *et al*., 2019) [30]. By regulating osmolyte accumulation, triggering antioxidant enzymes, and changing the expression of stress-responsive genes, *Bacillus altitudinis* NKA32, an aerobic bacterium with ACC deaminase activity, decreased salt stress in rice (Bharti *et al*., 2024) [4].

Microbial mechanism of plant growth promotion

There are various ways to use microbes, such as PGPR, to encourage the growth of plants. The two most common approaches for stimulating plant growth are oblique and direct techniques. Through a number of methods, the indirect mechanism lessens the harmful effects of infections. The availability of numerous beneficial chemicals produced by microorganisms is the direct mechanism. By solubilising minerals, boosting nutrient availability, generating phytohormones and secreting siderophores, they also aid in the growth of their host plants. The following microorganisms assist the process of plant growth:

- Make nutrients more readily available
- Produce PGRs (cytokine, auxin and gibberellins)
- Metabolites like antibiotics, siderophores, 1-amino cyclopropane-1-carboxylate deaminase, and hydrogen cyanide
- Generalised resistance initiation (Duan *et al*., 2013) [11].

For instance, siderophore, HCN, IAA and phosphate solvents are all generated in the tomato rhizosphere Pseudomonas aeruginosa LES4 strain to encourage plant growth (Kumar *et al*., 2009) [26]. Despite these characteristics, microorganisms that support plant growth do so by generating the enzyme exopolysaccharides and antibiotics. Microorganisms produce the enzyme ACC deaminase, which converts acetylene into ammonia and a-ketobutyrate, shielding the host plant from ethylene's negative impacts (Glick, 2014) [19]. By creating biofilms and preventing the uptake of unwanted substances, exopolysaccharides shield host plants.

Role of soil microbial mycorrhizae

Mutual connections between fungi and deeper plant roots are termed mycorrhizae. The fungi that tend to be the most prevalent in farms are arbuscular mycorrhizae (AM). About 80% of species of higher plants have fungi. It is vital for the agricultural nutrient cycle. Likewise, mycorrhizae have an essential function in enhancing soil aggregation, plant nutrition, and physical attributes. Mycorrhizae create an array of metabolites under challenging circumstances, including amino acids, vitamins, minerals, and phytohormones.

The cumulative benefits of this connection include promoting plant growth and development under both typical and stressed conditions. Additionally, some studies have found that under stress conditions, mycorrhizal fungi affect plant physiology through osmoregulators. This mechanism involves carbon dioxide conversion, water usage effectiveness, and oxygen regulation. In conditions of drought, it additionally boosts the quantities of sugar and ions. According to what kind of stress, mycorrhizae are thought to execute various functions. Examples include fluctuations in Na^+ and K^+ acquisition during salt stress and nitrogen accessibility over drought (Hashem *et al*., 2016) [21].

Plants abiotic stress tolerance mechanisms aided by microbes

Plants respond to external shocks using a range of stress tolerance strategies, depending on the diversity underlying microbes (Elhindi *et al*., 2017) [15]. These bacteria flourish in the rhizosphere by consuming plant substances, and they generate critical biological materials such as gibberellins, enzymes, ABA, antifungal chemicals and other metabolites. Apart from effectively changing the nutrient profile, PGPM promotes productivity and metabolic rate by inducing the synthesis of phytohormones and their stimulating metabolites, oxygen mitigation, heavy metal accumulation, substrate induction, morphological and anatomical changes and determining physical features through the induction of volatile compounds.

Abiotic stress and its impact on plant productivity and soil health

Nutrients, water and temperature are all necessary for plants to thrive, but when these elements are insufficient or extreme, stress and lower productivity result. Abiotic stressors that modify the composition of soil and phytochemical reactions, such as shortages of salt, temperature extremes, nutrient deficiencies and pollution, interfere with plant metabolism and soil health. Heat stress promotes protein repairs and antioxidant responses; salt stress changes ion balance, reduces germination, and speeds up senescence; and water stress makes plants grow more slowly, generate shorter leaves and seeds, and flower later. While heavy metals harm proteins and reduce nutritional absorption, low temperatures impede physiological processes. Additionally, as demonstrated by the manufacture of reactive oxygen species, which improves a plant's susceptibility to specific illnesses, adaptations to abiotic stress can frequently increase exposure to bacterial stress.

Microbial mediation of abiotic stress

Plant growth-promoting rhizobacteria (PGPR), encompassing genera such as *Bacillus*, *Pseudomonas*, *Ochrobactrum*, *Enterobacter*, *Alcaligenes*, and *Jeotgalicoccus*, are well-documented for their capacity to augment plant growth and productivity under diverse abiotic constraints. These microbes facilitate stress mitigation through multifaceted mechanisms, including phosphate solubilisation, IAA biosynthesis, siderophore secretion, and 1-aminocyclopropane-1-carboxylate (ACC) deaminase activity, thereby enhancing nutrient bioavailability and alleviating ethylene-mediated stress responses.

Vesicular Arbuscular Mycorrhizae (VAM) symbioses substantially expand root absorptive surface area, improving phosphorus and micronutrient mobilisation, which is particularly critical under nutrient-deficient and stressed edaphic conditions.

Empirical evidence underscores the efficiency of PGPR in phytoremediation and stress tolerance. For instance, *Pseudomonas spp*. effectively mitigates the deleterious effects of heavy metals (Ni, Zn, Cu) by improving biomass accumulation and water-deficit tolerance through phosphate solubilisation and phytohormonal regulation. Arsenic-tolerant microbial consortia have been shown to enhance rice growth while restricting arsenic translocation to consumable tissues. Similarly, *Bacillus pumilus* confers salt and drought resilience in potato by upregulating antioxidative enzymes (catalase, peroxidase), maintaining chlorophyll integrity, and stimulating root proliferation. *B. amyloliquefaciens* significantly augments drought resilience in rice via enhanced root architecture and water uptake efficiency. Endophytic strains such as *B. altitudinis NKA32*, characterised by ACC deaminase activity, alleviate salinity stress by modulating osmolyte accumulation, antioxidant activation, and transcriptional regulation of stress-responsive genes.

Further, *Jeotgalicoccus huakuii* has demonstrated metabolic versatility by sustaining maize growth in saline environments through chlorophyll stabilisation and biomass enhancement. Additional genera (*Nocardia*, *Hydrogenomonas*, *Xanthomonas*, *Microbacterium*, and *Flavobacterium*) are implicated in xenobiotic degradation and hydrocarbon bioremediation, thereby mitigating pollutant-induced stress via co-metabolism, bioleaching, and bioaccumulation. In metal-contaminated soils, *Ochromobactrum sp. NBRISH6* not only improved maize yield but also elevated soil enzymatic activities (dehydrogenase, phosphatase) and induced host immune responses, indicating a dual role in remediation and yield improvement.

Microbial modulation of plant metabolites

Plants subjected to abiotic stress exhibit dynamic metabolic reprogramming of both primary and secondary metabolites. PGPR actively participate in this metabolic fine-tuning, thereby sustaining growth and productivity (Lugtenberg & Kamilova, 2009) [27]. Comparative metabolomic and proteomic analyses reveal substantial alterations in protein and metabolite profiles of stressed versus non-stressed plants. γ-Aminobutyric acid (GABA) plays a pivotal role in regulating C-N homeostasis, amino acid/carbohydrate metabolism, and developmental processes (Shelp *et al*., 2017) [38]. Furthermore, microbial taxa such as *Pseudomonas*, *Bacillus*, *Streptomyces*, and *Azospirillum* modulate phenolic biosynthesis, influencing plant defence and resilience.

Soil microbial biocontrol and consortia

Poly-microbial inoculation strategies provide synergistic benefits that surpass single-strain applications. Mixed inoculants comprising *Bacillus*, *Rhizobium*, and *Pseudomonas* significantly enhanced biomass accumulation and stress resilience relative to sole inoculations (Figueiredo *et al*., 2010) [18]. The *Rhizobium-Azospirillum* consortium upregulated nod gene expression and facilitated nodulation factor synthesis under saline regimes (Dardanelli *et al*., 2008) [10]. Likewise, co-inoculation of *Rhizobium* with *Bacillus megaterium* or *Pseudomonas striata* markedly improved yield, dry matter accumulation, and phosphorus assimilation, while simultaneously conferring tolerance to drought and salinity stress (Elkoca *et al*., 2010; Kaur *et al*., 2022) [16, 24].

Microbial role in biotic stress suppression

Although plants possess intrinsic structural and chemical defences, these are often inadequate against diverse phytopathogens. PGPR colonisation of the rhizosphere substantially fortifies host immunity by triggering systemic acquired resistance (SAR) and induced systemic resistance (ISR) (Salas-Marina *et al*., 2011) [37].

- SAR is mediated by salicylic acid accumulation and pathogen-related (PR) proteins.
- ISR operates through ethylene and jasmonic acid signalling and is often induced by non-pathogenic microbes via lipopolysaccharides and siderophores.

Upon activation, antioxidant and defence-related enzymes (peroxidase, catalase, superoxide dismutase, chitinase, phenylalanine ammonia lyase) are upregulated, safeguarding plants against reactive oxygen species and pathogen invasion. ISR and SAR may act synergistically to reinforce defence barriers across a broad spectrum of pathogens, including fungi, bacteria, and viruses (Choudhary & Johri, 2009; Wani *et al*., 2016; Beneduzi *et al*., 2012) [7, 45, 3].

PGPR and sustainable agroecosystems

Transitioning from conventional to sustainable agriculture necessitates the strategic deployment of PGPR as biofertilizers and bioprotectants. These beneficial microorganisms, including nitrogen-fixers and phosphate solubilisers, play crucial roles in nutrient cycling, soil fertility maintenance, and plant growth promotion (Peix *et al*., 2015) [31].

Their contributions encompass:

- Biological nitrogen fixation
- Phosphate and potassium mobilisation
- Synthesis of phytohormones (IAA, gibberellins, cytokinins) for morphogenesis
- Soil health maintenance through improved microbial community dynamics

Collectively, PGPR not only augment plant productivity but also foster resilience and ecological sustainability, rendering them indispensable agents in the paradigm shift toward climate-resilient agriculture.

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