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Nature's engineers: Harnessing microbial power for agricultural prosperity

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Abstract
Microorganisms play a vital role in agriculture and allied sectors, offering sustainable solutions to enhance productivity and environmental health. Beneficial microbes, such as nitrogen-fixing bacteria, mycorrhizal fungi, and phosphate-solubilizing microorganisms, are integral to improving soil fertility and nutrient cycling. These organisms also support plant growth by producing phytohormones, protecting against pathogens, and enhancing resistance to abiotic stresses like drought and salinity. Nitrogen-fixing bacteria reduce reliance on synthetic fertilizers by biologically converting atmospheric nitrogen into bioavailable forms for crops. Mycorrhizal fungi and phosphate-solubilizing microorganisms improve nutrient acquisition and soil health, supporting plant growth while mitigating chemical input usage. Microbial inoculants, including some biocontrol agents, suppress plant pathogens and pests, providing eco-friendly alternatives to chemical pesticides. In allied sectors, probiotics in livestock farming enhance animal gut health, immunity, and overall productivity, while aquaculture benefits from microbial applications to improve water quality, manage disease, and boost growth. Emerging applications include engineered microbes for carbon sequestration, sustainable biofuel production, and the development of biodegradable plastics. Additionally, microbes play a pivotal role in bioremediation, detoxifying polluted soils and water bodies, and in producing biofertilizers and biopesticides that support eco-friendly farming practices. These innovations underscore the potential of microbial solutions to address global challenges in food security, environmental sustainability, and agricultural resilience. Despite challenges such as strain competition and variable environmental conditions, advancements in microbial biotechnology and the integration of data-driven techniques like artificial intelligence offer promising opportunities.

Keywords: Microbial biotechnology, nitrogen fixation, biocontrol agents, probiotics, soil fertility, sustainable agriculture, bioremediation, biofertilizers, carbon sequestration, biofuels

1. Introduction

The most diverse biological systems on earth are soil microbial communities encompassing bacteria, fungi, actinomycetes, archaea, protozoa, microalgae and viruses (Fierer, 2017) [14]. These organisms normalize core ecosystem processes such as nutrient turnover, decomposition, organic matter formation, disease suppression, and plant-microbe signalling (Mendes *et al.*, 2013) [29]. Their contribution to agricultural productivity has been increasingly recognized as global concerns surrounding soil degradation, greenhouse gas emissions, biodiversity loss, and chemical overuse intensify (Tilman *et al*., 2002; Singh *et al* 2020). [55, 50] Modern agriculture heavily depends on nitrogen, phosphorus, and potassium fertilizers which donate to 40-60% of crop yields but also lead to eutrophication, soil acidification and declining microbial diversity (Vitousek *et al.*, 2013) [59]. Microbial biofertilizers and bio-stimulants offer eco-friendly alternatives improving nutrient use efficiency and restoring soil ecology (Bhattacharyya & Jha, 2012) [7]. Microorganisms are also central to plant resilience against abiotic stresses such as drought and salinity through hormonal regulation, osmolyte production and root architectural modification (Ngumbi & Kloepper, 2016) [32]. Microbial solutions extend beyond crop improvement. In livestock, probiotics enhance gut health and immunity (Krehbiel *et al.*, 2003) [24]. It has been shown in studies that microbial consortia can reduce ammonia, nitrate and pathogenic loads in aquaculture (Ringø *et al.*, 2020) [42]. Microorganisms has also been found to degrade pesticides, hydrocarbons and heavy metals providing cost-effective and sustainable bioremediation solutions in saving environment (Singh & Ward, 2004) [48]. Our understanding for soil microbiomes has been revolutionized by recent biotechnological advancements like metagenomics, metabolomics, synthetic biology, CRISPER, genome editing and AI-driven predictive modelling (Bender *et al*., 2016; Jansson & Hofmockel, 2020) [5, 21]. Given the centrality of microbes to agroecosystems and environmental sustainability, this review expands the earlier conceptual work to provide an extensive and evidence-based exploration of microbial contributions to agriculture.

2. Microbial Regulation of Soil Fertility and NUTRIENT Cycling

Microbial processes govern the transformation and mobilization of essential plant nutrients, playing a dominant role in biogeochemical cycles. Nearly all nitrogen, most phosphorus and significant proportions of sulphur and micronutrients become plant available only after microbial modifications (Richardson & Simpson, 2011; Kuypers *et al*., 2018) [41, 25].

2.1 Nitrogen-Fixing Microorganisms

2.1.1 Symbiotic and Free-living Nitrogen Fixation

Legume-rhizobium symbiosis is one of the most efficient biological nitrogen fixation (BNF) systems, contributing ~70-90 million tonnes of N annually (Herridge *et al*., 2008) [20]. Nodulation begins with flavonoids secreted by legume roots which induce bacterial *nod* genes producing lipochitooligosaccharide Nod factors (Oldroyd *et al*., 2011) [34]. Nod factors trigger cortical cell division and root hair curling enabling bacterial invasion through infection threads. Inside nodules, rhizobia differentiate into bacteroid and express the nitrogenase enzyme complex, composed of:

- Dinitrogenase reductase (Fe protein)
- Dinitrogenase (MoFe protein)

Nitrogenase reduces $N_2 \rightarrow NH_3$ under microaerobic conditions maintained by leghaemoglobin (Udvardi & Poole, 2013) [58]. Symbiotic N-fixation reduces the need for chemical fertilizers by 30-60% and improves soil organic nitrogen pools. Genera such as *Azospirillum*, *Herbaspirillum*, and *Burkholderia* associate with cereals and grasses, contributing both nitrogen fixation and phytohormone modulation (Bashan & de-Bashan, 2010) [3]. They enhance root length, surface area, and nutrient uptake. Free-living fixers such as *Azotobacter*, *Clostridium*, and heterocystous cyanobacteria (*Nostoc*, *Anabaena*) fix nitrogen independently in soil or aquatic environments (Saharan & Nehra, 2011) [46].

2.1.2 Biochemical Considerations

Nitrogenase enzyme is highly oxygen-sensitive. Microorganisms use various adaptations to ensure enzyme functionality under varying soil conditions such as Azotobacter shows high respiratory protection, Cyanobacteria have Glycolipid heterocyst walls and nearly all symbionts have oxygen buffering leghaemoglobin.

2.2 Phosphate-Solubilizing Microorganisms (PSMs)

Although soils contain abundant total phosphorus, only 1-2% is plant-available (Richardson & Simpson, 2011) [41]. PSMs increase soluble P via:

2.2.1 Organic Acid Secretion: *Pseudomonas*, *Bacillus*, *Penicillium*, and *Aspergillus* secrete gluconic, oxalic, citric, and malic acids, which chelate metal ions and release bound P (Khan *et al*., 2009) [21].

2.2.2 Phosphatase & Phytase Activity

Microbes mineralize organic P via:

- Acid phosphatases
- Alkaline phosphatases
- Phytases

2.2.3 Field Effects

PSMs increase P availability by 30-60% and enhance crop yields in cereals, legumes, and vegetables (Chen *et al*., 2006) [9].

2.3 Potassium- & Zinc-Solubilizing Microorganisms

Bacillus mucilaginosus, *Paenibacillus*, and *Frateuria aurantia* solubilize insoluble K and Zn compounds through:

- Polysaccharide secretion
- Organic acid production
- Chelation mechanisms (Basak & Biswas, 2009) [4]

2.4 Mycorrhizal Fungi

Arbuscular mycorrhizal fungi (AMF) colonize ~80% of plant species (Smith & Read, 2010) [51].

Roles of the Mycorrhizal Funi include:

- Improved P, Zn, Cu uptake
- Enhanced drought tolerance (Augé, 2001) [2]
- Increased root branching through strigolactone signaling
- Soil aggregation via glomalin-related soil proteins (GRSPs) (Rillig, 2004) [43]

2.5 Sulfur-Oxidizing and Other Nutrient-Mobilizing Microbes

Thiobacillus, *Paracoccus*, and *Beggiatoa* oxidize elemental sulfur to plant-available sulfate, improving nutrient uptake in alkaline soils (Shah *et al*., 2017) [47].

3. Plant Growth-Promoting Rhizobacteria (PGPR)

The diverse group of bacteria that colonize the rhizosphere, rhizoplane called Plant Growth Promoting Rhizobacteria (PGPR) does the so through multifaceted biochemical mechanisms. These bacteria influence the root architecture, availability of nutrients, hormonal balance and plant immunity thus making them essential components for sustainable agricultural systems (Kloepper & Schroth, 1981; Glick, 1995) [23, 15].

3.1 Direct Mechanisms OF PGPR

3.1.1 Phytohormone Production

One of the most well-established mechanisms is the synthesis of phytohormones particularly indole-3-acetic acid (IAA). Bacterial genera such as *Azospirillum*, *Pseudomonas* and *Bacillus* convert L-tryptophan exuded by plant roots into IAA via indole-3-pyruvate or indole-3-acetamide pathways (Spaepen & Vanderleyden, 2011) [52]. IAA enhances root hair proliferation, lateral root formation and overall root biomass changes that ultimately improve water and nutrient uptake (Patten & Glick, 2002) [36]. PGPR also synthesize gibberellins, cytokinins, polyamines and brassinosteroids each of which contribute to the cell division, stem elongation and seed germination (Bottini *et al*., 2004) [8]. These hormones modulate plant developmental processes and enhance vigor under stress conditions.

3.1.2 ACC-Deaminase Activity
ACC-deaminase (1-aminocyclopropane-1-carboxylate deaminase) is a stress-mitigating enzyme produced by several PGPRs including *Pseudomonas putida*, *Burkholderia cepacia* and *Enterobacter cloacae*. The enzyme cleaves ACC which is the precursor of ethylene into α-ketobutyrate and ammonia thereby lowering stress-induced ethylene levels (Glick *et al*., 2007) [7]. Reduced ethylene allows continuous root growth even under drought, flooding, salinity or heavy metal toxicity (Nadeem *et al*., 2014) [31].

3.1.3 Nitrogen Fixation
Non-symbiotic PGPR, especially *Azotobacter*, *Azospirillum* and certain *Bacillus* strains contribute measurable quantities of biologically fixed nitrogen in cereal crops providing an alternative to synthetic fertilizers (Bashan & de-Bashan, 2010) [3]. Though not as efficient as rhizobia they improve nitrogen use efficiency under field conditions.

3.1.4 Siderophore Production
PGPR synthesize siderophores such as pyoverdine, enterobactin and bacillibactin which chelate Fe^{3+} and make it more bioavailable to plants (Crowley, 2006) [10]. These high-affinity iron chelators also suppress pathogens by depriving them of essential iron.

3.1.5 Enhancing Nutrient Uptake
PGPR enhance phosphorus, potassium, zinc and iron availability via:

- Organic acid secretion
- Phytase production
- Mineral solubilizing enzymes

3.2 Indirect Mechanisms of PGPR
PGPR produce antibiotics such as phenazines, pyoluteorin, 2,4-diacetylphloroglucinol (DAPG) and hydrogen cyanide (HCN) which suppress soil-borne fungal pathogens (Haas & Défago, 2005) [18]. It has been shown in studies that the chitinases, proteases, cellulases, β-glucanases and lipases produced by PGPR degrade the structural components of fungal cell walls (Lorito *et al*., 2010) [26]. ISR is mediated through jasmonic acid (JA) and ethylene pathways providing broad-spectrum defence (Pieterse *et al*., 2014) [38]. *Pseudomonas fluorescens* has been known to primes host immunity without activating salicylic acid pathways. PGPR effectively colonize root surfaces, inhibiting pathogen attachment by competitive exclusion (Lugtenberg & Kamilova, 2009) [28].

4. Microbial Biocontrol Agents
4.1 Fungal Biocontrol Agents
Microbial biocontrol agents provide eco-friendly alternatives to chemical pesticides. Their mechanisms include parasitism, antibiosis, competition, and the activation of plant defences. Some fungal genera like *Trichoderma harzianum*, *T. viride*, and *T. atroviride* are widely used in agriculture. These genera show mycoparasitism by physical coiling and penetration of pathogenic fungi via appressoria. They produce hydrolytic enzymes like chitinases, glucanases and proteases which dissolve pathogenic cell walls. Few genera also produces secondary metabolites like gliotoxin and peptaibols which inhibit fungal growth. ISR induction had been carried by modulation of Jasmonic acid and Salicylic acid pathways. Some Entomopathogenic fungi like *Beauveria bassiana* and *Metarhizium anisopliae* infect insects by adhering to cuticles forming germ tubes and secreting chitinases and proteases to penetrate hosts.

4.2 Bacterial Biocontrol Agents
Few bacterial species such as *B. subtilis*, *B. amyloliquefaciens*, and *B. licheniformis* produce Lipopeptides (surfactin, iturin, fengycin), polyketides, volatile organic compounds (VOCs), These molecules inhibit pathogenic fungi and bacteria (Ongena & Jacques, 2008) [33]. *Pseudomonas fluorescens* produce siderophores, DAPG, HCN and phenazines. *P. fluorescens* suppresses pathogens like *Rhizoctonia solani*, *Pythium* and *Fusarium* (Haas & Défago, 2005) [18].

4.3 Viral and protozoan biocontrol agents
Baculoviruses target Lepidopteran pests with high specificity (Moscardi, 1999) [30]. Protozoan parasitoids suppress nematodes and soil pests (Stirling, 2014) [53].

5. Role of Microbes in Allied Agricultural Sectors
Probiotics such as *Lactobacillus*, *Bifidobacterium*, and *Enterococcus* improve gut microbiota balance, feed conversion ratio (FCR), immune modulation, vitamin synthesis (e.g., B12, K). Krehbiel *et al. (2003)* [24] demonstrated improved rumen fermentation efficiency with microbial feed additives. Aquaculture systems get benefitted from microbial consortia that degrade ammonia and nitrite (nitrifying bacteria), reduce algal blooms, suppress *Vibrio* spp. pathogens (Ringø *et al*., 2020) [42] and also improve water quality through bio-floc technology. Microbial enzymes (pectinases, cellulases, xylanases) enable fruit ripening control, reduced spoilage, biodegradable coatings and food safety improvement (Tripathi & Dubey, 2004) [57]. Microorganisms play indispensable roles beyond crop production, contributing significantly to livestock nutrition, aquaculture stability, post-harvest management, and food biotechnology. In livestock systems, probiotics such as *Lactobacillus*, *Bifidobacterium*, *Enterococcus*, *Streptococcus* and *Bacillus* spp. improve gut microbial balance, feed conversion ratio (FCR), nutrient absorption, immune modulation and vitamin synthesis—including B_{12}, riboflavin and vitamin K—by enhancing digestive enzyme activity, lowering gut pH and producing antimicrobial metabolites, with studies showing improved rumen fermentation efficiency and fibre digestion when microbial feed additives are used (Krehbiel *et al*., 2003) [24]. In aquaculture, beneficial microbial consortia play a central role in maintaining water quality and animal health; nitrifying and denitrifying bacteria such as *Nitrosomonas*, *Nitrobacter*, *Paracoccus* and *Pseudomonas* convert toxic ammonia to nitrate or nitrogen gas, while biofloc-forming microbes including *Bacillus* spp. assimilate nitrogen into microbial biomass, improving feed utilisation, growth performance and resistance to diseases, alongside strong suppression of *Vibrio* pathogens through competitive exclusion and antimicrobial metabolite production (Ringø *et al*., 2020; De Schryver & Verstraete, 2009) [42, 13]. Microbial

technology is equally vital in post-harvest management, where microbial enzymes such as pectinases, cellulases and xylanases derived from *Aspergillus*, *Penicillium* and *Bacillus* spp. facilitate controlled fruit ripening, peel softening, juice clarification, reduction of spoilage and development of biodegradable edible coatings made from microbial polymers like pullulan, xanthan gum and bacterial cellulose, thereby extending shelf life and limiting post-harvest losses (Tripathi & Dubey, 2004) [57]. Moreover, lactic acid bacteria used in fermented foods contribute to food safety through organic acid and bacteriocin production, while enhancing sensory qualities and generating bioactive compounds. Collectively, these microbial applications strengthen productivity, resilience and quality across livestock, aquaculture and food systems, making them essential components of sustainable agricultural development.

Figure 1: Microbial contributions to sustainable agriculture, illustrating key functional roles including nitrogen fixation, phosphate solubilization, plant growth promotion (PGPR), biocontrol mechanisms, bioremediation of pollutants, and emerging biotechnological applications such as synthetic biology and microbial carbon sequestration. (Adapted from Fierer 2017; Bender *et al.* 2016; Jansson & Hofmockel 2020) [14, 5, 21]

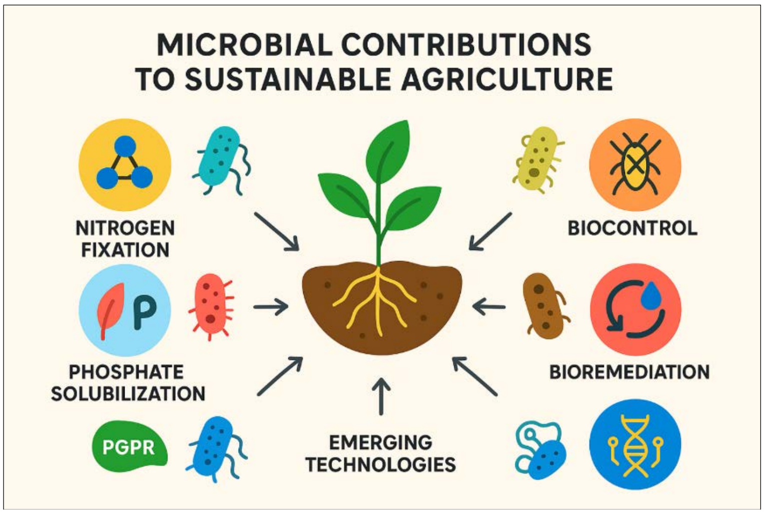

Fig 1: Microbial Contributions to Sustainable Agriculture

6. Emerging Technologies in Microbial Biotechnology

With the recent advancements in genomics, molecular biology, artificial intelligence and precision agriculture the perspective for microbial ecosystems have been dramatically enhanced. These technologies have enabled the development of more efficient, resilient and targeted microbial inoculants. Metagenomics based on shotgun sequencing or 16S/ITS amplicon sequencing allows characterization of entire microbial communities without culturing (Handelsman, 2004) [19]. Soil contains over 10^9 microbial cells per gram with thousands of uncharacterized taxa (Fierer, 2017) [14]. Discovery of novel P-solubilizers, N-fixers or biocontrol agents (Jansson & Hofmockel, 2020) [21] understanding rhizosphere signaling networks, tracking microbiome shifts during drought, salinity or fertilization and design of synthetic consortia for enhanced nutrient mobilization (Bender *et al.*, 2016) [5] are some of important applications in Agriculture. This emerging field focuses on manipulating community composition using targeted inoculation, soil conditioners promoting beneficial taxa, CRISPR-based editing of microbial genomes (Rubin *et al.*, 2022) [45] Synthetic biology enables the construction of “designer microbes” with engineered traits such as enhanced nitrogenase expression (Temme *et al.*, 2012) [54], which can improve phosphate solubilization pathways and stress-tolerance. CRISPR-Cas systems allow precise manipulation of microbial genomes to knock out inhibitory pathways, insert metabolic modules, enhance biosynthetic gene clusters (Zhu *et al.*, 2020) [60]. These technologies could create next-generation biofertilizers with predictable performance across field conditions. Nanotechnology improves biological inoculants through nano-encapsulation of PGPR or spores for longer shelf life, controlled nutrient release from nano-fertilizers, improved adhesion to seeds or soil particles. Nano-Si, nano-ZnO, and polymeric nanocarriers improve microbial survival under ultraviolet exposure and enhance colonization efficiency. AI models integrate soil data, weather patterns, and microbial traits to predict inoculant success under field conditions, optimize biofertilizer combinations, identify ideal environmental niches for microbial survival, forecast plant disease outbreaks based on microbiome signatures. Deep learning tools analyse massive genomic datasets to identify stress-tolerance genes, metabolic pathways, interspecies communication signals (microbial quorum sensing). Microbes contribute significantly to carbon cycling via Glomalin production by AMF (Rillig, 2004) [43], Bio-crust formation by cyanobacteria, Soil organic matter stabilization by actinomycetes and decomposers. Microbial engineering to enhance carbon sequestration is an emerging frontier in climate-smart agriculture.

7. microbial bioremediation & Environmental Restoration

Although microbial inoculants offer substantial benefits to plant productivity, soil fertility, and environmental sustainability, their widespread adoption in agriculture is constrained by several scientific, ecological, and socio-economic challenges. Variable field performance remains the most critical limitation, as microbial efficacy is strongly influenced by soil characteristics, climatic fluctuations, nutrient availability, crop genotypes, and interactions with native microbial communities, which often outcompete introduced strains and hinder their establishment in the rhizosphere (Bender *et al*., 2016; Trivedi *et al*., 2020) [5, 56]. Additionally, many commercial bioformulations suffer from poor shelf-life, inconsistent microbial viability, and limited tolerance to heat, UV exposure, and humidity, making storage and transport difficult in tropical environments. Farmers frequently encounter barriers such as limited awareness, lack of training, scepticism about efficacy, and inconsistent access to high-quality microbial products, while regulatory frameworks in many countries still lack standardized guidelines for biofertilizer purity, safety, and performance, creating disparities in market quality (Adesemoye & Kloepper, 2009) [1]. Despite these constraints, remarkable technological advancements are reshaping the future of microbe-enabled agriculture. The development of designer microbial consortia, optimized for specific crops and soil types, promises more resilient and predictable field performance, while novel seed-coating technologies, including polymeric, nano-enabled, and controlled-release coatings, substantially improve microbial survival, uniform root colonization, and field establishment (Pedrini *et al*., 2020) [37]. Synthetic biology and genome editing tools like CRISPR facilitate the development of stress-tolerant, efficient microbial strains capable of functioning under drought, salinity, and extreme temperatures, aligning microbial solutions with climate-smart agriculture goals. Advances in AI and machine learning are enabling precision biofertilization, where predictive models integrate soil microbiome profiles, weather data, and plant physiology to guide spatially accurate deployment of microbial products. Furthermore, the emerging concept of microbial carbon markets, where soil carbon sequestration mediated by microbial activity is quantified and monetized, creates new economic incentives for farmers and positions microbes at the centre of climate mitigation strategies. Together, these innovations show that although significant challenges persist, the future of microbe-based agriculture is rapidly evolving towards precision, resilience, and scalability.

8. Conclusion

Microorganisms are indispensable architects of agricultural ecosystems, contributing to nutrient cycling, plant growth promotion, disease suppression, soil structure enhancement, pollutant degradation, and climate resilience. Their ability to convert atmospheric nitrogen, solubilize phosphorus and potassium, produce growth-promoting phytohormones, and protect plants from pathogens through antagonism and systemic resistance makes them fundamental to ecological stability and sustainable productivity. As intensive agriculture continues to degrade soils, reduce biodiversity, and contribute to greenhouse gas emissions, microbe-based technologies offer regenerative alternatives that restore biological function while reducing chemical inputs. The convergence of metagenomics, synthetic biology, nano-formulation science, and artificial intelligence has dramatically transformed our capacity to harness microbial systems with precision, allowing the development of targeted consortia, engineered bioinoculants, and predictive tools for microbial deployment. However, to translate these advances into large-scale impact, coordinated efforts are required to strengthen regulatory frameworks, establish quality certification systems, improve supply chains, and expand farmer training programs. Future agricultural landscapes will rely heavily on microbial solutions not simply as supplements but as core components of nutrient management, climate adaptation, and soil restoration strategies. By integrating microbial technologies into mainstream agricultural practice, it is possible to build resilient, low-carbon, and resource-efficient food systems that safeguard both productivity and planetary health. Ultimately, microorganisms represent one of the most powerful yet underutilized assets for global food security, and their strategic application will shape the next generation of sustainable agriculture.

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