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A Manasa
Master' Student, Department of
Microbiology, College of
Agriculture, PJTAU,
Rajendranagar, Hyderabad,
Telangana, India

E Siddhartha
Master' Student, Department of
Microbiology, College of
Agriculture, PJTAU,
Rajendranagar, Hyderabad,
Telangana, India

V Akshaya
Master' Student, Department of
Microbiology, College of
Agriculture, PJTAU,
Rajendranagar, Hyderabad,
Telangana, India

N Siva Priya
Master' Student, Department of
Microbiology, College of
Agriculture, PJTAU,
Rajendranagar, Hyderabad,
Telangana, India

Dr. J Aruna Kumari
Principal Scientist, Department of
Biochemistry, AICRP on Forage
Crops, Agricultural research
institute, Rajendranagar,
Hyderabad, Telangana, India

Corresponding Author:
N Siva Priya
Master' Student, Department of
Microbiology, College of
Agriculture, PJTAU,
Rajendranagar, Hyderabad,
Telangana, India

Role of beneficial microorganisms in enhancing growth and productivity of forage crops: A review

A Manasa, E Siddhartha, V Akshaya, N Siva Priya and J Aruna Kumari

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Abstract

Forage crops are essential for sustainable livestock production by supplying nutritious feed that improves animal growth, milk and meat production and reproductive performance. They also enhance soil health, reduce erosion, support carbon sequestration and contribute to sustainable agriculture and food security (Qikun Liu *et al.*, 2025). Forage productivity is constrained by abiotic stress, biotic stress and climate change, which reduce biomass and forage quality. Sustainable improvement requires stress-tolerant cultivars, balanced nutrient management and climate-resilient agronomic practices (Wanlu Liu *et al.*, 2023). Beneficial microorganisms enhance plant growth and soil fertility by improving nutrient availability and increasing tolerance to biotic and abiotic stresses. Their use promotes sustainable agriculture by reducing reliance on chemical fertilizers and pesticides. Major beneficial microbial groups, including plant growth-promoting bacteria, arbuscular mycorrhizal fungi, actinomycetes and cyanobacteria, enhance forage crop growth by improving nutrient uptake, stress tolerance and disease resistance. Together, they improve soil fertility and support sustainable forage production. Beneficial microorganisms offer an eco-friendly approach to enhance forage productivity, soil health, nutrient use efficiency and stress tolerance while reducing dependence on chemical inputs. Future research should focus on developing efficient microbial consortia and advanced bioinoculants to support sustainable and climate-resilient forage production.

Keywords: Beneficial microorganisms, forage crops, PGPR, biofertilizers, mycorrhiza, nutrient uptake, sustainable agriculture

1. Introduction

Forage crops are the primary source of nutritious feed for livestock, improving animal growth, milk and meat production and reproductive performance (Capstaff and Miller, 2018) [9]. They also enhance soil fertility, reduce erosion, improve carbon sequestration and support sustainable crop-livestock systems (Sanderson *et al.*, 2013) [43]. Moreover, high-quality forages increase farm profitability and play a vital role in ensuring food security under changing climatic conditions (Mottet *et al.*, 2017; Thornton, 2010) [32, 53]. Globally, forage crops are essential for sustaining livestock production, but rising demand for animal products continues to exceed forage availability. In India, only about 4–5% of cultivated land is under fodder crops, resulting in significant deficits of green and dry fodder despite having the world's largest livestock population. Enhancing forage productivity through improved varieties and sustainable management practices is therefore crucial for ensuring fodder and livestock security (ICAR-IGFRI, 2013). Forage crop productivity is constrained by limited land availability, competition with food crops, poor-quality seed, inadequate irrigation, nutrient deficiencies and climate variability. In India, fodder shortages are further intensified by degraded grazing lands, seasonal rainfall dependence and low adoption of improved forage technologies. Enhancing forage production requires improved cultivars, efficient nutrient and water management and climate-resilient production practices. Beneficial microorganisms, including plant growth-promoting rhizobacteria (PGPR), arbuscular mycorrhizal fungi (AMF), nitrogen-fixing bacteria and phosphate-solubilizing microorganisms, enhance forage production by improving nutrient availability, stimulating root growth and producing phytohormones. These microbes increase forage biomass, improve nutritional quality, enhance tolerance to abiotic stresses and reduce dependence on chemical fertilizers, thereby promoting sustainable forage production systems

(Vessey, 2003; Richardson *et al.*, 2009; Backer *et al.*, 2018) [57, 38, 3]. This review aims to evaluate the role of beneficial microorganisms in enhancing the growth, productivity and quality of forage crops. It focuses on the mechanisms by which plant growth-promoting rhizobacteria (PGPR), arbuscular mycorrhizal fungi (AMF), nitrogen-fixing bacteria and phosphate-solubilizing microorganisms improve nutrient availability, plant growth and stress tolerance. The review also highlights recent advances in microbial biofertilizers, their contribution to sustainable forage production and identifies future research needs for improving forage productivity.

2. Forage crops: Importance and production constraints

2.1 Importance of the forage crops

Forage crops are the foundation of sustainable livestock production, providing a cost-effective source of nutritious feed essential for maintaining animal health, growth, reproduction and milk and meat production. They improve soil fertility through nitrogen fixation, enhance soil structure, reduce erosion and contribute to carbon sequestration, thereby supporting environmentally sustainable agriculture. In addition, forage crops increase farm profitability by reducing dependence on expensive concentrate feeds and strengthening integrated crop–livestock farming systems (Sanderson *et al.*, 2004) [43]. Forage crops play a significant role in soil conservation by providing continuous ground cover that reduces soil erosion caused by wind and water while improving soil structure and stability. Their extensive root systems enhance soil aggregation, increase water infiltration, promote organic matter accumulation and support beneficial soil microbial activity. Leguminous forages further improve soil fertility through biological nitrogen fixation, reducing the need for synthetic fertilizers and contributing to sustainable agricultural systems. Forage crops contribute significantly to carbon sequestration by capturing atmospheric carbon dioxide through photosynthesis and storing it in plant biomass and soil organic carbon. Their extensive and persistent root systems promote belowground carbon accumulation, improve soil organic matter and enhance long-term soil fertility. Well-managed perennial grasslands and forage-based systems also reduce greenhouse gas emissions while improving ecosystem resilience, making them an important component of climate-smart agriculture.

2.2 Major forage crops

Major forage crops include grasses such as Maize (*Zea mays*), Sorghum (*Sorghum bicolor*), Pearl millet (*Pennisetum glaucum*), Oats (*Avena sativa*) and Napier grass (*Cenchrus purpureus*), along with legumes such as Alfalfa (*Medicago sativa*), Berseem (*Trifolium alexandrinum*), Cowpea (*Vigna unguiculata*) and Lucerne. These crops are cultivated for their high biomass production, superior nutritional quality, palatability and adaptability to diverse agro-climatic conditions. Grass–legume combinations are widely recommended as they improve forage yield, protein content, soil fertility through biological nitrogen fixation and the sustainability of livestock production systems.

2.3 Constraints affecting forage productivity

Nutrient deficiencies, particularly of nitrogen, phosphorus, potassium and micronutrients such as zinc and sulfur, are major constraints limiting forage crop productivity and quality. Inadequate nutrient availability reduces chlorophyll synthesis, photosynthesis, root development, biomass accumulation and crude protein content, leading to poor forage yield and nutritional value. Continuous cultivation without balanced

fertilization further depletes soil fertility, while integrated nutrient management is essential to sustain forage production and soil health (Marschner, 2012; Fageria, 2014; Roy *et al.*, 2006; White and Brown, 2010) [58]. Soil degradation is also a major constraint to forage productivity, resulting from erosion, nutrient depletion, salinity, compaction and loss of soil organic matter. These processes deteriorate soil structure, reduce water-holding capacity, impair root development and limit nutrient availability, leading to lower forage yield and quality. Unsustainable land use, overgrazing and intensive cultivation further accelerate soil degradation, emphasizing the need for integrated soil fertility management and conservation practices to sustain forage production (Lal, 2004; Brady and Weil, 2017; FAO and ITPS, 2015; Montgomery, 2007). Climate change has become a constraint to forage productivity by increasing temperatures, altering rainfall patterns and increasing the frequency of droughts, floods and other extreme weather events. These changes reduce forage biomass, impair seed germination, shorten the growing season and decrease forage nutritional quality through reduced protein content and digestibility. Climate-induced stresses also affect soil moisture, nutrient availability and pest and disease incidence, thereby threatening the sustainability of forage-based livestock systems (Thornton *et al.*, 2009; IPCC, 2022; Hatfield and Prueger, 2015; Dumont *et al.*, 2015) [53, 1]. Pests and diseases are major biotic constraints that significantly reduce forage crop yield, quality and persistence. Insect pests, fungal, bacterial and viral pathogens damage leaves, stems and roots, impairing photosynthesis, nutrient uptake and biomass production. Climate change and intensive cultivation have further increased the incidence and severity of these biotic stresses, resulting in substantial economic losses and reduced forage availability. Adoption of resistant cultivars, integrated pest management (IPM), crop rotation and biological control measures is essential for sustainable forage production (Strange and Scott, 2005; Oerke, 2006; Savary *et al.*, 2019; Lucas, Hawkins and Fraaije, 2015).

2.4 Beneficial microorganisms associated with forage crops

Beneficial microorganisms associated with forage crops include plant growth-promoting rhizobacteria (PGPR) such as *Azospirillum brasilense*, *Azotobacter chroococcum*, *Bacillus subtilis*, *Bacillus megaterium*, *Pseudomonas fluorescens* and *Paenibacillus polymyxa*; symbiotic nitrogen-fixing bacteria including *Rhizobium leguminosarum*, *Sinorhizobium (Ensifer) meliloti* and *Bradyrhizobium japonicum*; arbuscular mycorrhizal fungi (AMF) such as *Rhizophagus irregularis* (formerly *Glomus intraradices*), *Funneliformis mosseae* (formerly *Glomus mosseae*) and *Claroideoglomus etunicatum*; and endophytic microorganisms including *Herbaspirillum seropedicae*, *Burkholderia phytofirmans* and *Trichoderma harzianum*. These beneficial microbes enhance biological nitrogen fixation, phosphorus and zinc solubilization, phytohormone production, nutrient uptake, stress tolerance and suppression of soil-borne pathogens, thereby improving forage biomass, nutritional quality and soil fertility while reducing dependence on chemical fertilizers (Vessey, 2003; Smith and Read, 2008; Lugtenberg and Kamilova, 2009; Pandove *et al.*, 2023; Andrade *et al.*, 2023) [57, 50, 30, 34, 14].

3. Beneficial Microorganisms Associated with Forage Crops

3.1 Nitrogen-Fixing Microorganisms

Nitrogen-fixing microorganisms are among the most important beneficial microbes associated with forage crops, as they convert atmospheric nitrogen into plant-available ammonia through

biological nitrogen fixation. Symbiotic bacteria such as *Rhizobium leguminosarum*, *Ensifer* (*Sinorhizobium*) *meliloti*, *Bradyrhizobium japonicum* and *Mesorhizobium* spp. establish root nodules in forage legumes including Alfalfa (*Medicago sativa*), Clovers (*Trifolium* spp.) and Forage peas (*Pisum sativum*), while free-living and associative diazotrophs such as *Azospirillum brasilense*, *Azotobacter chroococcum*, *Herbaspirillum seropedicae* and *Gluconacetobacter diazotrophicus* enhance nitrogen availability in forage grasses. These microorganisms improve forage biomass, crude protein content, nitrogen-use efficiency and soil fertility, thereby reducing the dependence on synthetic nitrogen fertilizers and promoting sustainable forage production (Vessey, 2003; Herridge *et al.*, 2008; Pandove *et al.*, 2023) [57, 21, 34].

3.2 Arbuscular Mycorrhizal Fungi (AMF)

Arbuscular mycorrhizal fungi (AMF), predominantly *Rhizophagus irregularis* (formerly *Glomus intraradices*), *Funneliformis mosseae* (formerly *Glomus mosseae*), *Claroideoglomus etunicatum*, *Gigaspora margarita* and *Acaulospora laevis*, form mutualistic associations with the roots of most forage crops, significantly enhancing nutrient and water uptake. AMF improve the acquisition of relatively immobile nutrients, particularly phosphorus, zinc and copper, while enhancing root growth, drought tolerance and resistance to salinity and soil-borne pathogens. In forage legumes and grasses, AMF symbiosis increases biomass production, crude protein content, nutrient-use efficiency and soil aggregation through the production of glomalin, thereby contributing to sustainable forage productivity and soil health (Smith and Read, 2008; Smith and Smith, 2011; Begum *et al.*, 2019; Chandrasekaran *et al.*, 2019) [50, 51, 7, 11].

3.3 Phosphate-Solubilizing Microorganisms (PSM)

Phosphate-solubilizing microorganisms (PSM) comprise beneficial bacteria such as *Bacillus megaterium*, *Bacillus subtilis*, *Pseudomonas fluorescens*, *Pseudomonas putida*, *Rhizobium leguminosarum* and *Enterobacter cloacae*, along with fungi including *Aspergillus niger*, *Penicillium bilaiae* and *Trichoderma harzianum*, which convert insoluble soil phosphates into plant-available forms through the secretion of organic acids and phosphatase enzymes. In forage crops, these microorganisms enhance phosphorus uptake, stimulate root development, improve biomass production and increase forage quality while reducing the requirement for chemical phosphorus fertilizers. Furthermore, PSM often act synergistically with arbuscular mycorrhizal fungi and nitrogen-fixing bacteria to improve nutrient-use efficiency, soil fertility and sustainable forage production under nutrient-deficient conditions (Rodríguez and Fraga, 1999; Richardson *et al.*, 2009; Sharma *et al.*, 2013; Alori *et al.*, 2017) [39, 38, 49, 2].

3.4 Potassium-Solubilizing Microorganisms (KSM)

Potassium-solubilizing microorganisms (KSM) include beneficial bacteria such as *Bacillus mucilaginosus*, *Bacillus edaphicus*, *Bacillus circulans*, *Paenibacillus glucanolyticus*, *Pseudomonas fluorescens* and *Burkholderia* spp. as well as fungi including *Aspergillus niger* and *Aspergillus terreus*, which release potassium from insoluble silicate minerals through the production of organic acids, exopolysaccharides and chelating compounds. In forage crops, these microorganisms enhance potassium availability, promote root growth, improve water-use efficiency, increase photosynthetic activity and enhance

tolerance to drought and other abiotic stresses, resulting in greater forage biomass and quality. Moreover, KSM act synergistically with nitrogen-fixing bacteria and phosphate-solubilizing microorganisms to improve nutrient-use efficiency, soil fertility and sustainable forage production while reducing dependence on chemical potassium fertilizers (Basak and Biswas, 2009; Meena *et al.*, 2016; Etesami *et al.*, 2017; Sattar *et al.*, 2019) [6, 31, 16, 47].

3.5 Zinc-Solubilizing Bacteria (ZSB)

Zinc-solubilizing bacteria (ZSB) comprise beneficial rhizobacteria such as *Bacillus aryabhattai*, *Bacillus subtilis*, *Bacillus megaterium*, *Pseudomonas fluorescens*, *Pseudomonas putida*, *Enterobacter cloacae* and *Acinetobacter* spp. which convert insoluble zinc compounds (ZnO , $ZnCO_3$ and $Zn_3(PO_4)_2$) into plant-available Zn^{2+} ions through the secretion of organic acids, siderophores and chelating metabolites. In forage crops, ZSB improve zinc uptake, stimulate root growth, enhance chlorophyll synthesis, enzyme activity and protein metabolism, resulting in increased biomass production, forage nutritional quality and tolerance to abiotic stresses. Furthermore, ZSB exhibit multiple plant growth-promoting traits, including phosphate solubilization, indole-3-acetic acid (IAA) production and siderophore synthesis, making them promising biofertilizers for improving micronutrient-use efficiency and sustainable forage production (Saravanan *et al.*, 2007; Ramesh *et al.*, 2014; Kamran *et al.*, 2017; Hussain *et al.*, 2020) [45, 37, 25, 23].

3.6 Endophytic Microorganisms

Endophytic microorganisms include beneficial bacteria such as *Herbaspirillum seropedicae*, *Azoarcus* spp., *Burkholderia phytofirmans*, *Bacillus subtilis*, *Pseudomonas fluorescens* and *Enterobacter* spp., as well as fungi including *Trichoderma harzianum*, *Piriformospora indica* (*Serendipita indica*), *Epichloë* spp., and *Penicillium* spp. which colonize internal plant tissues without causing disease. In forage crops, these endophytes promote plant growth through biological nitrogen fixation, phytohormone production, nutrient solubilization, siderophore synthesis and induction of systemic resistance against pathogens. They also enhance drought, salinity and heat tolerance, improve nutrient-use efficiency, increase forage biomass and nutritional quality and contribute to sustainable forage production by reducing the dependence on chemical fertilizers and pesticides (Ryan *et al.*, 2008; Hardoim *et al.*, 2015; Santoyo *et al.*, 2016; White *et al.*, 2019) [40, 20, 44, 58].

3.7 Cyanobacteria and Actinomycetes

Cyanobacteria such as *Anabaena* spp., *Nostoc* spp., *Calothrix* spp., *Oscillatoria* spp., and *Aulosira fertilissima*, together with actinomycetes including *Streptomyces* spp., *Micromonospora* spp., *Frankia* spp., and *Nocardia* spp. play significant roles in enhancing soil fertility and forage crop productivity. Cyanobacteria contribute through biological nitrogen fixation, production of extracellular polysaccharides and secretion of growth-promoting substances, whereas actinomycetes improve nutrient cycling, produce antibiotics, siderophores, hydrolytic enzymes and phytohormones that suppress soil-borne pathogens and stimulate plant growth. In forage production systems, these beneficial microorganisms improve soil structure, nutrient availability, forage biomass and stress tolerance, thereby supporting sustainable and eco-friendly crop production with reduced dependence on chemical fertilizers and pesticides (Barka *et al.*, 2016; Rai *et al.*, 2000) [5, 36].

3.8 Biocontrol Microorganisms

Biocontrol microorganisms associated with forage crops include bacterial species such as *Bacillus subtilis*, *Bacillus amyloliquefaciens*, *Pseudomonas fluorescens*, *Pseudomonas chlororaphis* and *Streptomyces* spp. together with fungal antagonists such as *Trichoderma harzianum*, *Trichoderma viride*, *Trichoderma asperellum*, *Clonostachys rosea* and *Gliocladium virens*. These beneficial microorganisms suppress soil-borne pathogens through mechanisms including antibiosis, competition for nutrients and ecological niches, production of hydrolytic enzymes (chitinase, cellulase, β -1,3-glucanase), mycoparasitism and induction of systemic resistance in plants. In forage crops, biocontrol microbes reduce the incidence of diseases caused by *Fusarium*, *Rhizoctonia*, *Pythium* and *Sclerotinia* species, while simultaneously enhancing root development, nutrient uptake, forage biomass and quality, making them environmentally friendly alternatives to chemical pesticides (Compant *et al.*, 2005; Lugtenberg and Kamilova, 2009; Woo *et al.*, 2014) [12, 30, 59].

4. Mechanisms of Plant Growth Promotion by Beneficial Microorganisms

Beneficial microorganisms promote forage crop growth through multiple direct and indirect mechanisms. Direct mechanisms include biological nitrogen fixation by *Rhizobium*, *Azospirillum* and *Azotobacter*; solubilization of phosphorus, potassium and zinc by *Bacillus*, *Pseudomonas* and *Enterobacter* spp.; production of phytohormones such as indole-3-acetic acid (IAA), gibberellins and cytokinins; siderophore production and ACC deaminase activity, which collectively enhance nutrient uptake, root architecture and plant growth. Indirectly, microorganisms such as *Trichoderma* spp., *Bacillus subtilis* and *Pseudomonas fluorescens* suppress pathogens through antibiosis, competition, hydrolytic enzyme production and induction of systemic resistance, while arbuscular mycorrhizal fungi improve water relations and nutrient acquisition. These integrated mechanisms enhance forage biomass, nutritional quality, stress tolerance and soil health, making beneficial microorganisms indispensable for sustainable forage production (Vessey, 2003; Lugtenberg and Kamilova, 2009; Glick, 2012; Richardson *et al.*, 2009; Backer *et al.*, 2018) [57, 30, 19, 38, 3].

4.1 Biological Nitrogen Fixation

Biological nitrogen fixation (BNF) is a key mechanism by which beneficial microorganisms convert atmospheric nitrogen (N_2) into plant-available ammonia through the nitrogenase enzyme complex. Symbiotic diazotrophs such as *Rhizobium leguminosarum*, *Ensifer* (*Sinorhizobium*) *meliloti*, *Bradyrhizobium japonicum* and *Mesorhizobium* spp. form root nodules in forage legumes, while associative and free-living bacteria including *Azospirillum brasilense*, *Azotobacter chroococcum*, *Herbaspirillum seropedicae* and *Gluconacetobacter diazotrophicus* contribute to nitrogen availability in forage grasses. Biological nitrogen fixation enhances plant nitrogen uptake, chlorophyll synthesis, crude protein content, biomass production and soil fertility, thereby reducing dependence on synthetic nitrogen fertilizers and promoting sustainable forage production (Herridge *et al.*, 2008; Vessey, 2003) [22, 57].

4.2 Solubilization and Mobilization of Nutrients

Beneficial microorganisms enhance forage crop growth by solubilizing and mobilizing essential nutrients that are otherwise unavailable in the soil. Phosphate-solubilizing bacteria such as

Bacillus megaterium, *Pseudomonas fluorescens* and *Enterobacter* spp., potassium-solubilizing bacteria including *Bacillus mucilaginosus* and *Bacillus circulans*, zinc-solubilizing bacteria such as *Bacillus aryabhattai* and *Pseudomonas putida*, arbuscular mycorrhizal fungi (*Rhizophagus irregularis* and *Funneliformis mosseae*) increase the availability and uptake of phosphorus, potassium, zinc and other micronutrients through the production of organic acids, phosphatases, siderophores, chelating compounds and extensive hyphal networks. These mechanisms improve root development, nutrient-use efficiency, forage biomass and nutritional quality while reducing dependence on chemical fertilizers, thereby supporting sustainable forage production (Rodríguez and Fraga, 1999; Richardson *et al.*, 2009; Sharma *et al.*, 2013; Etesami *et al.*, 2017; Smith and Read, 2008) [39, 38, 49, 16, 50].

4.3 Production of Plant Growth Regulators

Beneficial microorganisms promote forage crop growth through the production of plant growth regulators (PGRs), including auxins (indole-3-acetic acid, IAA), gibberellins, cytokinins, abscisic acid and modulation of ethylene levels via ACC deaminase. Rhizobacteria such as *Azospirillum brasilense*, *Azotobacter chroococcum*, *Bacillus subtilis*, *Bacillus megaterium*, *Pseudomonas fluorescens*, *Enterobacter cloacae* and endophytes like *Herbaspirillum seropedicae* synthesize these phytohormones, stimulating root elongation, lateral root formation, seed germination, nutrient uptake and overall plant vigor. The production of ACC deaminase further alleviates stress-induced ethylene accumulation, enhancing tolerance to drought, salinity and other environmental stresses. Collectively, microbial production of plant growth regulators improves forage biomass, nutritional quality and resilience while reducing the need for synthetic growth-promoting chemicals (Spaepen *et al.*, 2007; Glick, 2012; Dodd *et al.*, 2010; Vessey, 2003; Backer *et al.*, 2018) [52, 19, 15, 57, 4].

4.4 Siderophore Production

Siderophore production is an important plant growth-promoting mechanism exhibited by beneficial microorganisms such as *Pseudomonas fluorescens*, *Pseudomonas putida*, *Bacillus subtilis*, *Bacillus amyloliquefaciens*, *Azotobacter chroococcum*, *Burkholderia cepacia* and *Streptomyces* spp. which synthesize low-molecular-weight iron-chelating compounds under iron-limiting conditions. These siderophores enhance iron availability to forage crops while simultaneously restricting iron acquisition by phytopathogens, thereby suppressing disease development. In addition, siderophore-producing microorganisms improve nutrient uptake, chlorophyll synthesis, photosynthetic efficiency, root growth and stress tolerance, ultimately increasing forage biomass and nutritional quality. Thus, siderophore-producing microbes play a crucial role in sustainable forage production by promoting plant nutrition and providing effective biological control against soil-borne pathogens (Ahmed and Holmström, 2014; Saha *et al.*, 2016; Glick, 2012; Lugtenberg and Kamilova, 2009) [1, 41, 19, 30].

4.5 ACC Deaminase Activity

ACC deaminase activity is an important plant growth-promoting mechanism exhibited by rhizobacteria such as *Pseudomonas fluorescens*, *Pseudomonas putida*, *Bacillus subtilis*, *Bacillus amyloliquefaciens*, *Azospirillum brasilense*, *Enterobacter cloacae*, *Variovorax paradoxus* and *Burkholderia phytofirmans*. These microorganisms produce the enzyme 1-aminocyclopropane-1-carboxylate (ACC) deaminase, which

degrades ACC, the immediate precursor of ethylene, thereby lowering stress-induced ethylene levels in plants. Reduced ethylene concentration promotes root elongation, nutrient uptake and plant growth under drought, salinity, flooding, heavy metal toxicity and other abiotic stresses. Consequently, ACC deaminase-producing microorganisms improve forage biomass, nutrient-use efficiency and stress resilience, making them valuable bioinoculants for sustainable forage crop production (Nascimento *et al.*, 2018) [33].

4.6 Production of Extracellular Enzymes

Beneficial microorganisms associated with forage crops produce extracellular enzymes such as cellulases, chitinases, β -1,3-glucanases, proteases, pectinases, phosphatases, amylases and lipases, which play vital roles in nutrient cycling and plant protection. Bacteria including *Bacillus subtilis*, *Bacillus amyloliquefaciens*, *Pseudomonas fluorescens*, *Streptomyces* spp. and fungi such as *Trichoderma harzianum*, *Trichoderma viride* and *Penicillium* spp. secrete these enzymes to degrade complex organic matter, mineralize nutrients and lyse the cell walls of phytopathogenic fungi. Consequently, extracellular enzyme production enhances nutrient availability, improves soil fertility, suppresses soil-borne diseases and promotes root growth, forage biomass and crop resilience. These multifunctional activities make enzyme-producing microorganisms valuable bioinoculants for sustainable forage production systems (Compant *et al.*, 2005; Lugtenberg and Kamilova, 2009; Jacoby *et al.*, 2017) [12, 30, 24].

4.7 Exopolysaccharide Production

Exopolysaccharide (EPS)-producing microorganisms such as *Azospirillum brasilense*, *Rhizobium leguminosarum*, *Sinorhizobium (Ensifer) meliloti*, *Bacillus subtilis*, *Bacillus amyloliquefaciens*, *Pseudomonas fluorescens*, *Paenibacillus polymyxa* and *Enterobacter* spp., secrete high-molecular-weight polysaccharides that improve soil aggregation, moisture retention and root colonization in forage crops. EPS enhances microbial survival under drought, salinity and other environmental stresses by forming protective biofilms around roots, while facilitating nutrient acquisition and strengthening plant-microbe interactions. Additionally, EPS contributes to improved soil structure, increased water-use efficiency, enhanced root growth and greater forage biomass and quality, making EPS-producing microorganisms valuable bioinoculants for sustainable forage production.

4.8 Induced Systemic Resistance (ISR)

Induced systemic resistance (ISR) is a defense mechanism activated by beneficial microorganisms such as *Pseudomonas fluorescens*, *Pseudomonas putida*, *Bacillus subtilis*, *Bacillus amyloliquefaciens*, *Bacillus velezensis*, *Trichoderma harzianum*, *Trichoderma asperellum* and *Streptomyces* spp. which stimulate the plant immune system without causing disease. These microorganisms trigger Jasmonic acid (JA) and Ethylene (ET)-dependent signaling pathways, leading to enhanced production of defense enzymes, pathogenesis-related proteins, phytoalexins and antioxidant compounds that protect forage crops against bacterial, fungal and viral pathogens. Besides improving disease resistance, ISR enhances plant vigor, nutrient uptake, stress tolerance and forage yield, thereby reducing reliance on chemical pesticides and contributing to sustainable forage production (Pieterse *et al.*, 2014; Van Wees *et al.*, 2008; Conrath *et al.*, 2006; Lugtenberg and Kamilova, 2009) [35, 54, 13, 30].

4.9 Biological Control of Plant Pathogens

Biological control of plant pathogens is an important mechanism by which beneficial microorganisms protect forage crops from diseases while promoting plant growth. Beneficial bacteria such as *Bacillus subtilis*, *Bacillus amyloliquefaciens*, *Pseudomonas fluorescens*, *Pseudomonas chlororaphis* and *Streptomyces* spp., together with fungi including *Trichoderma harzianum*, *Trichoderma asperellum*, *Trichoderma viride* and *Clonostachys rosea*, suppress pathogens through antibiosis, competition for nutrients and ecological niches, production of siderophores and lytic enzymes, mycoparasitism and induction of systemic resistance. These microorganisms effectively control major soil-borne pathogens such as *Fusarium* spp., *Rhizoctonia solani*, *Pythium* spp., *Sclerotinia sclerotiorum* and *Macrophomina phaseolina*, thereby enhancing root health, nutrient uptake, forage biomass and quality while reducing dependence on chemical fungicides and supporting sustainable forage production (Compant *et al.*, 2005; Lugtenberg and Kamilova, 2009; Köhl *et al.*, 2019) [12, 30, 26].

5. Role of Beneficial Microorganisms in Improving Soil Health

Beneficial microorganisms such as *Rhizobium leguminosarum*, *Azospirillum brasilense*, *Azotobacter chroococcum*, *Bacillus subtilis*, *Pseudomonas fluorescens*, *Rhizophagus irregularis*, *Funneliformis mosseae*, *Trichoderma harzianum* and *Streptomyces* spp. play a pivotal role in improving soil health by enhancing nutrient cycling, organic matter decomposition, biological nitrogen fixation and the solubilization of phosphorus, potassium and micronutrients. These microorganisms also improve soil aggregation through the production of exopolysaccharides and glomalin, increase soil microbial diversity and enzymatic activity, suppress soil-borne pathogens and enhance soil carbon sequestration. Consequently, microbial inoculation improves soil fertility, water-holding capacity, soil structure and long-term sustainability of forage production systems while reducing the dependence on chemical fertilizers and pesticides (Van der Heijden *et al.*, 2008; Jacoby *et al.*, 2017) [54, 24].

5.1 Improvement of Soil Fertility

Beneficial microorganisms such as *Rhizobium leguminosarum*, *Azospirillum brasilense*, *Azotobacter chroococcum*, *Bacillus subtilis*, *Bacillus megaterium*, *Pseudomonas fluorescens*, *Rhizophagus irregularis*, *Funneliformis mosseae* and *Trichoderma harzianum* significantly improve soil fertility by enhancing biological nitrogen fixation, solubilization of phosphorus, potassium and zinc and accelerating organic matter decomposition. These microorganisms increase soil enzyme activities, microbial biomass, nutrient cycling and the availability of essential macro- and micronutrients while improving soil aggregation through the production of exopolysaccharides and glomalin. Consequently, microbial inoculation enhances soil organic carbon, cation exchange capacity, water-holding capacity and overall soil productivity, leading to sustained forage crop growth and reduced dependence on chemical fertilizers (Van der Heijden *et al.*, 2008; Richardson *et al.*, 2009; Jacoby *et al.*, 2017) [54, 38, 24].

5.2 Enhancement of Soil Organic Matter

Beneficial microorganisms such as *Trichoderma harzianum*, *Bacillus subtilis*, *Bacillus amyloliquefaciens*, *Streptomyces* spp.,

Azotobacter chroococcum, *Rhizobium leguminosarum*, arbuscular mycorrhizal fungi (*Rhizophagus irregularis* and *Funneliformis mosseae*) and cellulolytic fungi including *Aspergillus* spp., accelerate the decomposition of plant residues and organic amendments, thereby increasing soil organic matter (SOM). These microorganisms produce extracellular enzymes such as cellulases, ligninases, xylanases and phosphatases that convert complex organic materials into stable humus while enhancing microbial biomass carbon and nutrient mineralization. In addition, AMF contribute to soil carbon sequestration through the production of glomalin, which stabilizes soil aggregates and protects organic carbon from decomposition. Consequently, microbial activity improves soil organic carbon content, nutrient availability, soil structure and long-term fertility, thereby supporting sustainable forage crop production (Lehmann and Kleber, 2015; Van der Heijden *et al.*, 2008; Jacoby *et al.*, 2017) [28, 54, 24].

5.3 Improvement of Soil Structure

Beneficial microorganisms such as *Rhizophagus irregularis*, *Funneliformis mosseae*, *Bacillus subtilis*, *Pseudomonas fluorescens*, *Azospirillum brasilense*, *Rhizobium leguminosarum*, *Trichoderma harzianum* and *Streptomyces* spp., play a crucial role in improving soil structure by promoting soil aggregation through the production of glomalin, exopolysaccharides (EPS) and fungal hyphae that bind soil particles into stable aggregates. These microorganisms enhance soil porosity, aeration, water infiltration, moisture retention and resistance to erosion while facilitating root penetration and microbial activity. Improved soil aggregation also increases carbon sequestration and nutrient retention, thereby enhancing soil resilience, fertility and long-term productivity of forage production systems (Smith and Read, 2008) [50].

5.4 Improvement of Soil Enzyme Activities

Beneficial microorganisms such as *Bacillus subtilis*, *Bacillus amyloliquefaciens*, *Pseudomonas fluorescens*, *Azotobacter chroococcum*, *Rhizobium leguminosarum*, *Trichoderma harzianum*, *Streptomyces* spp. and arbuscular mycorrhizal fungi (*Rhizophagus irregularis* and *Funneliformis mosseae*) significantly enhance soil enzyme activities by stimulating the production of dehydrogenase, urease, phosphatase, β -glucosidase, cellulase, protease and arylsulfatase enzymes. These enzymes accelerate the decomposition of organic matter, nutrient mineralization and the cycling of carbon, nitrogen, phosphorus and sulfur, thereby improving soil fertility and nutrient availability. Increased enzyme activities also reflect higher microbial biomass and biological activity, leading to improved soil quality, root growth and forage productivity while reducing dependence on chemical fertilizers (Jacoby *et al.*, 2017) [24].

5.5 Rhizosphere Microbial Diversity

Rhizosphere microbial diversity comprises a wide range of beneficial bacteria, fungi, actinomycetes and archaea, including *Bacillus subtilis*, *Pseudomonas fluorescens*, *Azospirillum brasilense*, *Rhizobium leguminosarum*, *Burkholderia* spp., *Streptomyces* spp., arbuscular mycorrhizal fungi (*Rhizophagus irregularis* and *Funneliformis mosseae*) and *Trichoderma harzianum*, which interact synergistically to support forage crop growth. A diverse rhizosphere microbiome enhances nutrient cycling, biological nitrogen fixation, organic matter decomposition, disease suppression and plant tolerance to abiotic stresses while maintaining soil ecological balance.

Greater microbial diversity also increases soil enzyme activities, improves nutrient-use efficiency, stabilizes soil structure and enhances resilience against environmental disturbances, ultimately leading to higher forage productivity and long-term soil sustainability.

5.6 Influence on Growth and Productivity of Forage Crops

Beneficial microorganisms such as *Rhizobium leguminosarum*, *Azospirillum brasilense*, *Azotobacter chroococcum*, *Bacillus subtilis*, *Pseudomonas fluorescens*, *Rhizophagus irregularis*, *Funneliformis mosseae*, *Trichoderma harzianum* and *Bacillus aryabhattai* significantly enhance the growth and productivity of forage crops by improving nutrient availability, biological nitrogen fixation, phytohormone production and stress tolerance. These microorganisms stimulate seed germination, root development, chlorophyll synthesis, photosynthetic efficiency and nutrient uptake, leading to increased plant height, tillering, leaf area, dry matter accumulation and forage yield. They also improve forage quality by increasing crude protein content, digestibility and mineral composition while reducing the need for chemical fertilizers. Consequently, microbial inoculation enhances both the quantity and nutritional quality of forage crops, supporting sustainable livestock production and long-term agricultural productivity (Vessey, 2003; Richardson *et al.*, 2009; Backer *et al.*, 2018; Schütz *et al.*, 2018) [57, 38, 3, 48].

5.7 Improvement in Forage Quality

Beneficial microorganisms such as *Rhizobium leguminosarum*, *Azospirillum brasilense*, *Azotobacter chroococcum*, *Bacillus subtilis*, *Pseudomonas fluorescens*, arbuscular mycorrhizal fungi (*Rhizophagus irregularis* and *Funneliformis mosseae*) and *Trichoderma harzianum* significantly improve forage quality by enhancing nutrient uptake, nitrogen fixation and phytohormone production. These microorganisms increase crude protein, digestible dry matter, mineral content (Ca, P, Zn and Fe), chlorophyll concentration and improve fiber composition by reducing neutral detergent fiber (NDF) and acid detergent fiber (ADF), thereby enhancing forage palatability and digestibility. Improved nutrient assimilation and stress tolerance also result in higher concentrations of essential amino acids and better nutritional value for livestock. Consequently, microbial inoculation enhances both forage yield and feed quality, contributing to improved animal productivity and sustainable forage-based livestock systems (Vessey, 2003; Smith and Read, 2008; Schütz *et al.*, 2018; Backer *et al.*, 2018) [57, 50, 48, 4].

6. Conclusion

Beneficial microorganisms, including *Rhizobium*, *Azospirillum*, *Azotobacter*, *Bacillus*, *Pseudomonas*, arbuscular mycorrhizal fungi, *Trichoderma*, endophytes, cyanobacteria and actinomycetes, play a pivotal role in enhancing the growth, productivity and nutritional quality of forage crops through biological nitrogen fixation, nutrient solubilization, phytohormone and siderophore production, ACC deaminase activity, biological control of pathogens and improvement of soil health. These microorganisms enhance nutrient-use efficiency, forage biomass, crude protein content, stress tolerance, soil fertility and rhizosphere microbial diversity while reducing dependence on chemical fertilizers and pesticides, thereby contributing to sustainable forage production. Although challenges such as variable field performance and formulation stability remain, advances in microbial consortia, biofertilizer technologies and microbiome-based approaches offer promising opportunities for improving forage productivity and resilience.

Therefore, the integration of beneficial microorganisms into forage production systems represents an environmentally sustainable and economically viable strategy for supporting long-term agricultural productivity, livestock nutrition and global fodder security.

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