Chapter 10
Prolific Microbial Agents as Key Products for Sustainable Agriculture

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Abstract The current agricultural system is confronted with the challenge of excessive reliance on chemical-based fertilizers and pesticides. While these inputs have revolutionized agriculture, they also pose significant environmental risks. As a result, the utilization of agriculturally important microorganisms has become imperative to ensure sustainable agriculture in an environmentally friendly manner. These microorganisms can serve as biofertilizers, offering a wide range of plant growth-stimulating traits such as nitrogen fixation, nutrient solubilization, synthesis of siderophores and phytohormones, etc. By establishing symbiotic relationships, they enhance soil fertility, improve nutrient availability, and promote plant growth, thereby reducing the rely on synthetic fertilizers. Moreover, beneficial microorganisms act as natural adversaries to pests, providing an alternative to chemical pesticides. Microbes also enhance crop resilience to abiotic stresses such as drought and salinity through the production of stress-tolerant compounds, modulation of plant hormones, and improved nutrient uptake efficiency. Furthermore, they contribute to climate-smart agriculture by sequestering carbon in the soil, thereby mitigating greenhouse gas emissions. The use of microbial consortia further enhances plant

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growth, disease suppression, and stress tolerance. Additionally, microorganisms play an imperative role in biofortifying food crops, improving nutrient absorption, and addressing malnutrition. In summary, microorganisms offer diverse applications in sustainable agriculture, providing transformative solutions for crop-based food production.

Keywords Abiotic stress · Agriculturally important microorganisms · Beneficial microorganisms · Biofertilizers · Crops · Microbial consortia

10.1 Introduction

Sustainable agriculture has attracted a lot of attention recently as a way to meet the rising global food demand while reducing the negative environmental effects of traditional farming practices, which rely on chemical fertilizers and pesticides. In this context, the incorporation of microorganisms into agricultural systems has emerged as a promising and comprehensive strategy, in which agriculturally important microbes can be used as biofertilizers and biopesticide agents and ensure eco-friendly agricultural practices [1, 2]. However, the intricate interplay among microorganisms, plants, and soil forms the basis of the microbial-plant-soil nexus, which is fundamental to sustainable agriculture. In order to fully explore the potential of agriculturally important microorganisms for sustainable crop production, it is important to understand their mechanisms of action. These microorganisms possess diverse traits and functions that contribute to improved plant growth, improved nutrient availability, and improved soil health [3, 4]. By elucidating these mechanisms, targeted strategies can be developed to optimize their effectiveness and application in agricultural systems. The utilization of microorganisms as biofertilizers is a noteworthy application in the realm of sustainable agriculture. Microorganisms possessing diverse plant growth-promoting characteristics, including nitrogen fixation and phosphate solubilization, play a vital role in enhancing soil fertility and nutrient accessibility [5]. Biofertilizers facilitate nutrient uptake and augment crop productivity by creating symbiotic relationships with plants, thereby mitigating the need for synthetic fertilizers and their associated environmental hazards [6]. In addition, microorganisms have enormous potential as biocontrol agents in pest control. Beneficial microorganisms can act as natural enemies of pests, inhibiting their growth, reproduction, and pathogenicity [7]. This biological control approach offers an environmentally friendly alternative to chemical pesticides and minimizes negative impacts on ecosystems and human health. The ability of crops to withstand abiotic stresses such as drought, salinity, and extreme temperatures is essential for ensuring sustainable agricultural production [8]. Various mechanisms have been identified through which microorganisms can enhance plant tolerance and adaptation to stress [3, 8, 9]. Some of the methods used to enhance plant growth and resilience include producing stress-tolerant compounds, modifying plant hormone levels, and enhancing nutrient uptake efficiency [10]. Integrating these stress-tolerant microorganisms into agricultural practices offers prospective options for maintaining crop yields in challenging environments. In addition, the application of microbial-based products shows potential for implementing climate-smart agricultural practices. Microbial organisms have the ability to sequester carbon within the soil, thereby decreasing the amount of greenhouse gas especially carbon dioxide and serving as a means of climate change mitigation [11]. Microbial consortia, consisting of compatible microorganisms, have demonstrated increased synergistic impacts on plant growth and productivity. Microbial consortia are now an efficient way for improving crop growth, disease suppression, and stress tolerance in plants compared to single microbial inoculants, by utilizing the various functional properties of different microorganisms [12]. Microbial inoculants are also important for biofortifying food crops, which can help alleviate global malnutrition and enhance human health [13–15]. They have the potential to improve the absorption and availability of vital nutrients, including iron, zinc, and selenium, in crops [16]. This improvement enhances the nutritional quality of crops, addressing nutrient deficiencies in vulnerable populations.

This chapter sheds light on the diverse roles of microorganisms as key components in sustainable agriculture and highlights their immense potential for various applications. Comprehensive understanding and effective use of microorganisms are critical to unlocking transformative and long-lasting solutions for sustainable plant-based food production.

10.2 The Microbial-Plant-Soil Nexus: A Holistic Approach to Sustainable Agriculture

The microbial-plant-soil nexus embodies a comprehensive and scientifically sound tactic to achieving the goals of sustainable agriculture. It recognizes the complicated interactions between microorganisms, plants, and soil within agricultural ecosystems [17]. This approach highlights the use of beneficial microbes in augmenting plant growth, soil health, and promoting sustainable agricultural practices. Microorganisms play a key and indispensable role in nutrient cycling, a fundamental process in agricultural systems [18]. They actively contribute in the decomposition of complex organic matter, breaking it down into simpler forms that can be readily absorbed by plants [19]. Moreover, microorganisms contribute to nitrogen fixation, converting atmospheric N into a biologically usable form for plants. Through these processes, microorganisms improve nutrient accessibility, thereby promoting plant growth and reducing the need for synthetic fertilizers [20]. Furthermore, microorganisms exert a profound influence on soil structure and health. They actively contribute to the formation of soil aggregates, which enhance soil structure, porosity, and water infiltration [21]. These improvements in soil structure, in turn, enhance soil fertility and nutrient retention capacity. Additionally, certain microbes possess plant growth-promoting traits such as phytohormone production, nutrient solubilization, and facilitation of nutrient uptake by plants [2]. The microbial-plant-soil nexus also plays a crucial role in disease suppression within agricultural systems. Beneficial microorganisms act as natural antagonists against plant pathogens by actively competing for resources, producing antimicrobial compounds, and inducing systemic resistance in plants [22]. These activities effectively reduce the occurrence and severity of plant diseases. By harnessing biocontrol agents derived from microorganisms, farmers can minimize the use of chemical pesticides, which can have detrimental effects on the environment and human health [7]. Various strategies can be implemented to fully harness the potential of the microbial-plant-soil nexus. One such strategy involves the application of microbial biofertilizers, which contain beneficial microorganisms that enhance nutrient availability and promote plant growth [2]. These biofertilizers can be applied to seeds, roots, or soil to establish thriving and beneficial microbial communities, ultimately enhancing overall crop productivity. Furthermore, biopesticides derived from microorganisms offer an environmentally friendly alternative for pest control. Microbial-based biopesticides, such as *Bacillus thuringiensis* (Bt) and entomopathogenic fungi, specifically target pests while minimizing harm to nontarget organisms and reducing the risk of pest resistance development [23]. Integrating the microbial-plant-soil nexus into sustainable agricultural systems necessitates the adoption of soil management practices that support microbial activity [17]. This includes minimizing soil disturbance, maintaining soil organic matter through cover cropping and crop rotation, and reducing the use of chemical inputs that can disrupt microbial communities. By implementing these practices, farmers can foster a healthy and productive microbial ecosystem within the soil.

10.3 Understanding the Mechanisms of Action of Agriculturally Important Microorganisms

Agriculturally important microorganisms show imperative contribution in augmenting plant growth through diverse arrays of mechanisms. These microorganisms exert both direct and indirect influences on plant growth and development. Directly, they facilitate plant growth via phytostimulation and bio-fertilization. On the contrary, in the indirect way, they function as “bio-pesticides” or “biocontrol” agents [24]. The direct mechanisms employed by agriculturally important microorganisms encompass the facilitation of nutrient uptake and enhancement of nutrient availability. They possess the capacity to fix nitrogen [25], solubilize phosphorus and other essential mineral nutrients [26], and mineralize organic compounds [24]. Moreover, these microorganisms produce phytohormones such as “IAA,” “ethylene,” “cytokinins,” and “gibberellins,” which elicit plant growth responses [27]. The production of siderophores, which facilitate iron uptake, can be regarded as both a direct and indirect mechanism [28]. In addition to their direct effects, agriculturally important microorganisms exhibit indirect mechanisms that contribute to the promotion of plant growth. These encompass the production of antibiotics and hydrolytic enzymes, which help in combating plant pathogens and supporting plant health [29]. They also have the capability to induce systemic resistance in plants, thereby enhancing defense mechanisms against pathogens [8]. Furthermore, these microorganisms secrete exopolysaccharides (EPS), which foster soil aggregation and improve soil structure, ultimately benefiting plant growth [30].

The multifaceted activities of agriculturally important microorganisms establish them as precious contributors to plant growth and development. By harnessing these beneficial interactions, these microorganisms present promising prospects for promoting sustainable agriculture and ensuring ecological balance.

10.4 Microbial Agents as Biofertilizers for Improving Crop Productivity

Biofertilizers, classified as organic fertilizers, consist of microbial strains possessing plant growth-promoting characteristics. The excessive use of chemical-based fertilizers in recent years has raised concerns about their detrimental effects on the environment. Consequently, there is a growing public interest in adopting eco-friendly strategies. Utilizing biofertilizers is revolutionizing agricultural practices by providing an environmentally sustainable approach and reducing dependence on agrochemicals. This transformation hinges upon the careful selection of microbial strains to ensure optimal results. Microbial strains, including bacteria, fungi, and mycorrhizae such as "*Bacillus*," "*Rhizobium*," "*Lactobacillus*," '*Azotobacter*," "*Pseudomonas*," "photosynthetic bacteria," "*Trichoderma* sp., "*Glomus* sp.," "*Gigaspora* sp.," "*Pezizella* sp.," and "yeasts" exhibit a wide range of capabilities, such as nitrogen fixation, solubilization of phosphate, zinc, iron, and potassium, as well as the production of phytohormones and cellulolytic enzymes [2, 31–33]. These strains are primarily utilized as biofertilizers [2, 33]. Through the processes of nitrogen fixation, phosphate, potassium, and zinc solubilization, secretion of plant growth-regulating substances like hormones and vitamins and facilitation of organic matter biodegradation, biofertilizers play a crucial role in augmenting the plant growth and also contribute in maintaining soil health [2, 34]. Biofertilizers are widely acknowledged as microbial inoculants that effectively enhance nutrient availability in the soil, addressing the multifaceted challenges stemming from intensive chemical fertilizer usage [35]. In addition to their role in facilitating nutrient uptake by plants, biofertilizers exert a significant influence on various vital plant physiological processes, including the augmentation of water absorption and the promotion of photosynthetic rates [36]. Extensive research has documented the capacity of biofertilizers to enhance both abiotic and biotic stress tolerance in plants [8, 37]). Moreover, they play a pivotal role in the bioremediation of pesticides, contributing to the mitigation of their environmental impact [38–40]. Functioning as effective biocontrollers and biofertilizers exhibit noteworthy antagonistic properties against a diverse range of soil-borne plant pathogens, encompassing *Rhizoctonia* root rot, chill wilt, *Pythium* root rot, mung bean root rot, and parasitic nematodes [2, 41]. Advancements in bioformulation technologies are imperative for the successful commercialization of proficient microbial strains that possess biocontrol and plant growth-promoting capabilities. Several essential characteristics define an exemplary biofertilizer: (1) it must demonstrate environmental friendliness; (2) the microbial strains employed in its formulation must be nonpathogenic; (3) it should provide crops with high-quality nutrients; and (4) it should exhibit an extended shelf life [2, 42]. The meticulous selection of microorganisms possessing desirable traits stands as a pivotal factor in biofertilizer production. A comprehensive understanding of the interactions between microorganisms, crops, and the environment is vital to enhance crop growth [2, 43]. Microbes utilized in bioformulations undergo rigorous testing under in situ and in vivo conditions to ascertain the preservation of desired properties and the attainment of desired outcomes [44]. Furthermore, the chosen microbes for biofertilizer formulation should exhibit genetic stability, target specific crops, maintain synchrony with the native microbial population, and demonstrate survivability even in the absence of a host [5, 45]. The development of biofertilizers has traditionally focused on single microbial strains, but recent research emphasizes the advantages of employing multiple strains in the form of microbial consortia. These consortia act synergistically through diverse mechanisms, resulting in heightened effectiveness for crop enhancement [46, 47]. The process of biofertilizer development is intricate and requires rigorous assessments to meet stringent quality standards. Ensuring the viability of microorganisms is of paramount importance, enabling them to sustain soil fertility even after extended periods of storage [2, 48]. Biofertilizers can be formulated as dried powder, granules, or liquid, utilizing different carrier materials to support microbial growth and facilitate efficient delivery [49]. Liquid biofertilizers, in particular, can incorporate specialized cell protectants to extend their shelf life and require lower application dosages compared to other formulations [50]. The selection of an appropriate carrier material is a critical consideration, as it plays a significant role in preserving cell viability during storage and transportation [51]. The ideal carrier material should be nontoxic, possess high moisture absorption and water retention capacities, have a prolonged shelf life, and be easily processable [52]. Encapsulation of the inoculants with the carrier material ensures convenient handling, efficacy, and long-term storage capabilities [53].

The evaluation of biofertilizer efficacy can vary based on crop specificity. Various strategies can be employed, including seed treatment and soil application, for the utilization of specific biofertilizers [54]. In the context of paddy cultivation, seedling treatment with biofertilizers emerges as the preferred approach [55]. Following the application of biofertilizers to the soil, seeds, or roots, microorganisms establish colonization in the vicinity of the roots, thereby promoting growth in the targeted crop [56]. The root exudates excreted by plants facilitate the proficient colonization of microorganisms within the rhizosphere, optimizing their establishment and function [45].

10.5 Microbes as Biocontrol Agents and Their Potential for Pest Management

Pest management plays a pivotal role in modern agriculture and ecosystem preservation. However, traditional methods of pest control relying on chemical pesticides have proven to be environmentally harmful, posing risks to ecosystems, human health, and nontarget organisms [57–59]. Consequently, there is a growing interest in developing sustainable and eco-friendly alternatives for pest management. Microbes, including bacteria, fungi, viruses, and nematodes, have emerged as promising biocontrol agents due to their effective pest control capabilities while minimizing the negative impacts associated with conventional approaches [60]. For over a century, the study of microbes and their role in the health of living beings has been widely recognized. In modern agriculture, microbes have gained prominence as natural pesticides when combined with hybrid seeds, high-yield varieties, and regular irrigation, making them a leading trend in the agricultural sector [61]. Researchers are exploring sustainable methods to safeguard crops from insects and pathogens while enhancing soil health by harnessing the power of beneficial microorganisms. These microorganisms serve as natural biocontrol agents, inhibiting the growth of harmful pests and diseases while promoting plant growth and development [62, 63]. Among the bacteria used in agriculture, *Bacillus thuringiensis* (Bt) has long been employed due to its insecticidal proteins, making it a valuable and environmentally friendly biopesticide. Recent studies have suggested its potential use as a biofertilizer to enhance plant growth and its application in the development of transgenic plants (Liliana [64, 65]). *Pseudomonas chlororaphis* isolates are also utilized as biopesticides, providing protection to plants against a wide range of microbial pathogens, insects, and nematodes [66]. Entomopathogenic fungi (EPF) offer an environmentally sustainable approach to biocontrol against insect pests [67]. With over 700 species identified from approximately 90 different genera, these fungi have the ability to infect and induce disease in insects under favorable conditions [67]. Notable strains include *Beauveria bassiana*, *Metarhizium anisopliae*, *Hirsutella*, *Isaria*, *Lecanicillium*, and *Beauveria* [68, 69]. These fungi produce spores that attach to the pest's cuticle, penetrate it, and ultimately lead to the pest's demise. Fungal biocontrol agents are particularly effective against pests such as aphids, whiteflies, and thrips, and they offer a lower risk of developing resistance compared to chemical pesticides [67]. Insect-specific viruses, such as nucleopolyhedroviruses and granuloviruses, have shown great potential as biocontrol agents. These viruses selectively infect and eliminate their host insects [70, 71]. Microbial biocontrol agents provide numerous benefits for pest management. They demonstrate precise targeting, effectively controlling pests while minimizing harm to beneficial organisms. Moreover, these agents are environmentally friendly and pose no toxicity risks to humans. They also have the advantage of rapid degradation, reducing the potential for persistent residues in soil, water, and food [60]. Furthermore, their utilization supports sustainability and organic farming practices by decreasing reliance on synthetic pesticides. They can be seamlessly integrated into pest management programs, complementing other control methods.

10.6 Microbial Role in Enhancing Crop Resilience to Abiotic Stresses

Abiotic stress has emerged as a significant global concern, causing substantial agricultural losses on a widespread scale [72]. It encompasses the detrimental effects of nonliving environmental factors that impose stress on various species. These factors comprise extreme light conditions (both high and low), radiation (UV-B and UV-A), temperature fluctuations (both high and low), water-related challenges (drought, flooding, and submergence), chemical influences (heavy metals and pH), salinity resulting from excessive Na + levels, deficiency or excess of essential nutrients, gaseous pollutants (such as ozone and sulfur dioxide), mechanical factors, and other less common stressors [73]. These stressors can manifest individually or in combination. In agricultural settings, crops and plants regularly encounter stress due to a complex interplay of these factors, resulting in distinct effects [72, 74]. The accumulation of heavy metals in plants has detrimental consequences for their growth, photosynthetic activity, and crop yield [75]. Salinity stress disrupts various physiological processes, including seed germination, seedling establishment, vegetative growth, ionic toxicity, osmotic pressure, and oxidative damage [76–78]. Drought stress adversely affects key components of photosynthesis, such as photosystem-I and photosystem-II, and impairs the functionality of enzymes like ascorbate peroxidase, glutathione reductase, and superoxide dismutase [79]. Cold stress induces cell and tissue dehydration, crystallization of cellular water, reduced membrane conductivity, increased leakage of reactive electrolytes, decreased weight, and lower relative water content, ultimately leading to poor crop yield [80]. Plants require a unique response tailored to their environmental conditions to adapt to specific abiotic stress conditions. Recent research indicates that each abiotic stress situation necessitates a precise, personalized plant response, and the interaction of two or more stress factors may require a distinct response [72]. When two or more stresses occur simultaneously, an opposing response may be required. For instance, a common field scenario involves the combination of heat and drought stress. Under heat stress conditions, plants open stomata to cool the leaves through transpiration. However, when heat stress is combined with drought stress, plants are unable to open stomata, resulting in higher leaf temperatures [81]. Microbes employ various biochemical and molecular mechanisms to mitigate the adverse impacts of different abiotic stresses on plant growth and development [82].

Plants receive protection against abiotic stressors through various mechanisms employed by microorganisms. These include the synthesis of phytohormones, osmolytes, and exopolysaccharides (EPS), as well as the activity of 1--aminocyclopropane-1-carboxylate (ACC) deaminase and the induction of stress-responsive genes (Upadhayay et al., 2023). Plant-associated microorganisms, such as endophytes, arbuscular mycorrhizal fungi, and plant growth-promoting rhizobacteria [82], have been recognized for their ability to enhance crop yield and improve stress tolerance. Plant growth-promoting rhizobacteria (PGPR) play a vital role in this regard by producing phytohormones like indole-3-acetic acid (IAA), cytokinins, and abscisic acid. They also produce antioxidants such as superoxide dismutase (SOD), peroxidase (POD), ascorbate peroxidase (APX), catalase (CAT), and glutathione reductase (GR). Additionally, PGPR possess the enzyme ACC deaminase, which aids in the degradation of the ethylene precursor ACC, thereby helping to alleviate the adverse effects of abiotic stress and induce systemic tolerance [83, 84]. The presence of PGPR with ACC deaminase enzyme enables the regulation of ethylene production by converting ACC into alpha-ketobutyrate and ammonia, providing relief from stress [85]. AMF colonization has shown increased tolerance to water stress by enabling hyphae to reach water sources inaccessible to non-colonized plants via soil pores that are inaccessible to root hairs. Khalvati et al. [86] demonstrated water transport to the roots under drought conditions. Kavroulakis et al. [87] observed tolerance to water stress in *Solanum lycopersicum* cv ACE 55 by *Fusarium solani*, resulting in increased net CO_2 assimilation rate, enhanced antioxidant activity, and stomatal conductance. Mathur et al. [88] demonstrated drought resistance in *Triticum aestivum* through the colonization of *Rhizophagus intraradices* and *Funneliformis* spp., leading to increased relative water content, chlorophyll content, and restoration of electron transport in PS-II. *Bacillus* sp. and *Enterobacter* sp. provide drought tolerance in *Triticum aestivum* and *Zea mays* through the production of indole-3-acetic acid and salicylic acid [89]. *Funneliformis mosseae* enhances tolerance to low temperatures in *Solanum melongena* L. by improving photochemical reactions, activating the antioxidant defense system, accumulating protective molecules, and reducing membrane damage [90]. *Rhizoglomus intraradices* enhances salinity tolerance in *Pisum sativum* by improving nutrient uptake and promoting the accumulation of compatible osmolytes [91]. *Kocuria rhizophila* regulates plant hormones like abscisic acid and indole-3-acetic acid and improves nutrient acquisition, thereby providing salinity tolerance in Zea mays [92]. Table 10.1 illustrates the use of a various microbial strains to successfully mitigate a variety of stressors faced by plants.

10.7 Microbial Products and Soil Carbon Sequestration: A Pathway to Climate-Smart Agriculture

Climate change is a crucial global issue that has garnered significant attention from the scientific community worldwide. The primary driver behind climate change is human activities, which have contributed to a steady increase in global temperatures. Since the late nineteenth century, the Earth’s average surface temperature has risen by approximately 0.9 °C, largely attributed to the substantial surge in carbon dioxide

Table 10.1 Microbial-mediated approaches for mitigating abiotic stress in plants

Microorganism	Plant	Type of stress	Stress mitigation	References
Bacillus megaterium PB50	Rice	Drought stress	Improved growth under osmotic stress, protected from physical stress by stomatal closure	Arun et al. [93]
Arthrobacter woluwensis (AK1)	Soybean	Salinity stress	Salt-tolerant gene GmST1 is expressed with 42.85% expression	Khan et al. [13, 14]
Bacillus megaterium and *Pantoea agglomerans*	*Vigna radiata*	Drought and aluminum stress	The consortium decreased Al uptake and increased abiotic stress tolerance	Silambarasan et al. [94]
Compost + PGPR	Tomato	Drought stress	Enhancement in the plant growth, accumulation of osmolytes and minerals, decrease patterns in activity of antioxidant enzymes	Tahiri et al. [95]
Enterobacter cloacae PM23	Maize	Salinity stress	Augmentation in radial scavenging capacity, relative water content, soluble sugar, phenolic content, flavonoid content, and accumulation of osmolytes (glycine betaine, proline, etc.)	Ali et al. [96]
S. putrefaciens and *C. dubliniensis*	Pearl millet	Drought stress	Increase in relative water content, improvement in the level of proline accumulation, enhancement in the expression level of genes related to phytohormone biosynthesis, and drought-responsive transcription factors	Manjunatha et al. [97]
L. fusiformis and *L. sphaericus*	Maize	Cold stress	Increase in level of osmolytes, phytohormones, and phenolics, improvement in the activity of antioxidant enzymes	Jha and Mohamed [98]

(CO_2) emissions resulting from human-induced activities [99]. The period of industrialization, which commenced in the 1750s, witnessed a rapid and substantial rise in atmospheric CO_2 concentration from 277 to 400 parts per million (ppm) [99, 100]. Since around 1920, fossil fuel combustion has become the dominant contributor to CO_2 emissions, disrupting the natural carbon cycle and necessitating the implementation of carbon sequestration measures [99, 101]. Carbon sequestration refers to the process of capturing and storing atmospheric CO2 in the soil over an extended period. This method is predominantly achieved by incorporating crop residues and organic matter into the soil [102]. Additionally, indirect sequestration can occur through chemical reactions that transform CO_2 into inorganic compounds like "calcium carbonate ($CaCO_3$)" or "magnesium carbonates ($MgCO_3$)" [99, 103]. On the other hand, direct sequestration involves the fixation of CO2 into plant biomass through photosynthesis [104]. Various natural elements function as either carbon sources or sinks, depending on their capacity to absorb or release carbon. "Organic matter decomposition," "respiration and digestion activities," "volcanoes," and "water bodies" serve as natural carbon sources [105], while forests, photosynthesis, Earth's crust, soil, oceans, and freshwater bodies act as carbon sinks [99, 106]. Maintaining a balanced carbon cycle necessitates a proportional release of carbon from sources and sinks [107]. Carbon sequestration is influenced by a multitude of factors. These factors include the rate of production and decomposition of soil organic matter, the composition of the parent material, the position of the landscape, temperature and precipitation patterns, the presence of living organisms, and various management practices [99, 108]. Among these factors, SOM plays a significant role in modifying soil carbon stocks, thereby affecting the potential for soil sequestration [109]. Numerous processes contribute to the release and transport of SOM within the soil, influencing its physical, chemical, and biological characteristics, and ultimately impacting the potential for carbon sequestration [108]. The microbes found in rhizospheric soil, specifically known as "plant growth-promoting rhizobacteria" or "PGPR," have the capability to enhance soil microbial functioning, creating a positive contribution to global climate change. PGPR constitutes a significant portion of the overall microbial community and plays a crucial role in carbon sequestration [110]. The mechanisms by which PGPR mitigate climate change and sequester carbon involve multiple pathways [99]. PGPR plays a vital role in nutrient cycles, including those of "C" and "N" [111]. They exert improvement in the production of "glomalin" in the rhizospheric milieu by promoting mycorrhizal colonization [112]. Glomalin acts as an important reservoir of C and N in the soil [113]. Moreover, PGPR has the ability to directly enhance plant growth and allocate more C to plant biomass, thereby facilitating effective carbon recycling [99]. Additionally, research has shown that PGPR affects soil quality by regulating the amount of C in micro- and macroaggregates [112]. Soil microbial activities are directly or indirectly influenced by elevated temperature and carbon dioxide levels. High-temperature conditions enhance microbial activities, creating a positive feedback loop for climate change. Similarly, low moisture conditions can have comparable effects [114]. The maintenance of ecosystem C aggregation relies on achieving a balance between plant productivity and heterotrophic respiration, which is accomplished through the decomposition of SOM [99, 115].

Several studies have extensively documented the beneficial impacts of elevated CO_2 levels on plant growth, as well as the increased input of photosynthetic C into soils [116]. These increased carbon inputs can promote microbial growth, leading to an increase in soil microbial communities under elevated CO_2 [117]. Consequently, this may accelerate soil organic matter decomposition, potentially resulting in net carbon losses in the soil. Elevated carbon dioxide levels also stimulate rhizosphere priming effects, enhancing the decomposition of soil organic matter through microbial activity [118, 119]. The enzymatic activity of PGPR facilitates the decomposition of soil organic matter [120]. Moisture levels play a vital role in shaping the activities of microbial communities involved in climate change processes. In different soil environments, microbial activity tends to increase under conditions of drought and water stress. This response is primarily attributed to the decrease in water levels and the introduction of O_2 into previously oxygen-depleted soils [99]. Peatlands and wetlands are recognized as crucial reservoirs that store substantial amounts of C in terrestrial ecosystems [99, 121]. Consequently, the heightened degradation of resilient and stable organic matter under dry conditions can have significant implications for the global C cycle dynamics [122].

10.8 Microbial Consortia: An Effective Way for Plant Growth

The rhizosphere, a thriving area of soil, is teeming with a variety of different microorganisms. These subterranean microbes interact in complex ways both with each other and with plant roots, mutually benefiting plant growth. Plant signalling molecules such as root exudates play a crucial role and shape the rich spectrum of microbial diversity in this zone. The plant growth-promoting rhizomicrobes are a selected group of rhizosphere inhabitants that contribute to plant development through an impressive repertoire of mechanisms [12, 123]. From phosphate solubilization to nitrogen fixation to the production of plant growth hormones and antimicrobial compounds, these PGPRs serve as excellent substitutes for chemical inputs that often upset the delicate balance of soil biological and chemical properties. While biofertilizers typically feature a single microbial strain, pioneering research shows that the application of co-inoculation or consortium biofertilizers containing two or more microbial strains consistently produce more profound benefits for plant growth [12, 124]. Numerous scientific studies have advocated the utilization of microbial consortia as a promising approach to enhance plant growth, health, and survival, both under challenging environmental conditions and in natural settings [46, 47, 125, 126]. These consortia have been observed to stimulate plant roots, inducing the secretion of increased amounts of amino acids, growth regulators, and sugars. Moreover, they enhance the plant roots' ability to efficiently utilize minerals and other constituents present in the rhizosphere [46, 47, 124, 126]. This symbiotic interaction contributes to improved nitrogen fixation, thereby enabling plants to adapt to changes in environmental conditions more effectively [126]. Within the framework of field experiments, the inoculation of rice crops with a consortium comprising three distinct bacterial strains, namely, "*Burkholderia ubonensis* (la3c3)," "*Burkholderia vietnamiensis* (la1a4)," and "*Citrobacter bitternis* (p9a3m)," showed noteworthy improvement in both grain yield and quality and also reduced the use of nitrogen fertilizer by up to 25% [127]. In the study conducted by Kumar et al. [38–40], the tetra combination of *A. chlorophenolicus*, *B. megaterium*, *Enterobacter* sp., and *P. aeruginosa* exhibited significant improvements in plant height, grain yield, and straw yield for wheat under both greenhouse and field conditions. The application of a talc-based formulation including a consortium consisting of *K. pneumoniae*, *Erwinia* sp., and *P. nitritireducens* showed an extraordinary per-plant cumin seed yield (0.42 g). This notable formulation not only elevated essential agronomic parameters such as plant height, dry weight, and

100 seed weight but also resulted in a substantial enhancement in the overall yield, indicating a promising role of bacterial consortium in cumin cultivation [128]. A consortium comprising *Erwinia* sp. (nitrogen fixer), *C. arthrosphaerae* (phosphorus solubilizer), and *P. gessardii* (potassium solubilizer) enhanced growth and physiological parameters, including root/shoot length and biomass, chlorophyll, carotenoids, phenolics, flavonoids, and soluble sugar content in barley crops compared to the untreated control [129]. Tyagi et al. [130] showed that a tri-inoculant formulation ("*Serendipita indica*," '*Rhizophagus intraradices*," and "*Azotobacter chroococcum*") increased root and shoot length, fresh and dry weight, membrane electrolyte leakage, chlorophyll content, relative water content, and antioxidant enzyme activities (POX) significantly increased, CAT, PPO, SOD) in maize plants under drought conditions compared to the uninoculated control. The study by Kapadia et al. [131] showed that a microbial consortium consisting of *Bacillus* sp., *Delftia* sp., *Enterobacter* sp., and *Achromobacter* sp. significantly increased growth and mineral uptake of salt stressed tomatoes. The consortium treatment resulted in increased leaf, shoot and root dry weight, leaf count, shoot length, root length, secondary roots, and improved chlorophyll content compared to the control group, ultimately helping the plants to thrive in a saline environment.

10.9 Contribution of Microorganisms in Biofortification of Food Crops

To address the needs of an expanding world population, it is crucial to implement strategies that optimize biomass productivity. "Green revolution" has contributed a lot in terms of giving to higher crop yields. But a specific type of micronutrient deficiency, known as "hidden hunger," affects nearly half of the global population, leading to malnutrition [132]. In addition to macronutrients (N, P, K) and calories, essential micronutrients such as zinc, iron, selenium, etc. are vital for human health [15, 16]. The widespread presence of micronutrient deficiencies in low- and middle-income countries has a significant impact on human health [16, 133]. The lack of micronutrients poses a significant health burden, especially in regions with inadequate access to proper nutrition. According to the "United Nations System Standing Committee on Nutrition (UNSSCN, [134])," more than 50% of child mortality cases are directly or indirectly attributed to micronutrient deficiencies, which also contribute to major risk factors for maternal mortality [16]. Micronutrients such as iron (Fe), zinc (Zn), and selenium (Se) are essential for vital biological processes and must be obtained through the diet [13–15]. Inadequate intake of these micronutrients can lead to various health problems and increase the risk of developing several diseases [15, 16, 135].

Crop biofortification offers a promising solution to these challenges by enhancing the nutrient content of staple foods, particularly targeting low-income households that struggle to afford a diverse diet. Traditional approaches such as plant breeding, agronomic strategies, and genetic engineering have been employed for biofortification, but their effectiveness has been inconsistent, and they are laborious and costlier approaches [136]. In recent years, the utilization of naturally occurring soil microorganisms, specifically plant growth-promoting microbes like bacteria and mycorrhizal fungi, has emerged as a viable approach for crop biofortification ([3, 4, 45, 55] and 2022d). The interactions between plants and these microbes play a pivotal role in improving soil nutrition and facilitating the movement of micronutrients to different plant parts through processes such as solubilization, mobilization, and translocation of micronutrients [15, 16]. Microorganisms employ diverse strategies to enhance micronutrient uptake in plants, including the production of siderophores and other chelating substances, secretion of organic acids, proton extrusion, modification of root morphology and anatomy, reduction of antinutritional factors like phytic acid in food grains, secretion of phenolics and related compounds, and production of phytohormones as signaling molecules [3, 4, 16, 25, 45, 137]. The exploration of these potential plant growth-promoting (PGP) bacteria offers an alternative to chemical crop protection agents while also promoting environmental health and sustainability [13, 14, 138]. This makes them highly suitable for extensive use in organic agriculture. Several microorganisms have been identified and listed in Table 10.2 for their application in crop biofortification.

Table 10.2 Microbial-assisted biofortification of various crops

Microorganism	Micronutrient (s)	Plant	References
Zinc-solubilizing bacterial strains	Zinc	Wheat	Ali et al. [139]
Enterobacter sp. EG16	Selenium	Pak choi (*Brassica rapa* ssp. *chinensis*)	Yuan et al. [140]
Exiguobacterium sp. S17	Selenium	Brassica juncea (Indian mustard)	Marfetán et al. [141]
Consortium of *Bacillus subtilis*, *Bacillus aryabhattai*, and *Paenibacillus polymyxa*	Zinc and iron	Maize	Ahmad et al. [142]
Pseudomonas protegens	Zinc	Wheat	Singh et al. [3]
Three strains of Bacillus subtilis + soil applied iron	Iron	Groundnut	Sarwar et al. [143]
Bacillus altitudinis WR10	Iron	Wheat	Sun et al. [144]
Consortium (*Rhizobium* + plant growth-promoting rhizobacteria)	Iron	Lentil (*Lens esculenta*)	Kumar et al. [38–40]
Bacillus altitudinis	Zinc	Chickpea (*Cicer arietinum* L.)	Kushwaha et al. [145]
Bacillus mojavensis + *Bacillus cereus*	Iron	Sorghum	Mansani et al. [146]
S. marcescens FA-4	Zinc	Rice	Shakeel et al. [147]
Enterobacter sp. MN17 + Zn application	Zinc	*Kabuli* chickpea	Ullah et al. [148]

10.10 Challenges and Opportunities for Commercializing Microbial Products in Sustainable Agriculture

Microbe-based products, including biofertilizers and biopesticides, hold significant potential for sustainable agriculture. However, several challenges hinder their wide acceptance and successful implementation. To address them effectively, it is crucial to understand the issues faced by microbial-based products.

I. *Limited awareness and understanding*: One of the main obstacles faced by microbial-based products is the insufficient awareness and understanding among farmers, agronomists, and policy-makers regarding the advantages and appropriate utilization of these products. It is imperative to develop educational initiatives and outreach programs that effectively disseminate knowledge and enhance confidence in these innovative solutions.

II. *Regulatory hurdles*: Regulatory frameworks for microbial products often lack clarity or exhibit regional variations, which present a challenge in their commercialization. The lengthy and expensive registration processes further hinder manufacturers and limit market access. To overcome these obstacles, it is crucial to streamline regulations and establish clear guidelines that facilitate the smooth commercialization of microbial products.

III. *Product variability and efficacy*: The effectiveness of microbial products can be influenced by factors such as environmental conditions, crop species, and management practices, leading to variability in their performance. Ensuring consistent product efficacy across diverse agricultural systems and improving product stability are crucial challenges that require attention.

IV. *Quality control and standardization*: Maintaining product quality and standardization is critical to the successful commercialization of microbial products. The development of standardized production protocols, quality control measures, and certification programs will increase product reliability and consumer confidence.

V. *Limited scalability and production costs*: Manufacturing microbial products faces the challenge of increasing production and achieving cost efficiencies. Efficient production processes, optimized fermentation techniques, and research into alternative microbial strains are required to overcome these obstacles.

VI. *Market acceptance and competitiveness*: Microbial-based products compete with traditional agrochemicals that already dominate the market. It is crucial to convince farmers of the long-term benefits, cost-effectiveness, and environmental benefits of microbial products in order to achieve market acceptance and encourage their widespread use.

VII. *Research and development gaps*: Sustained research and development efforts are essential to identify and characterize novel microbial strains, refine formulation methods, and gain a comprehensive understanding of the complex interactions between microbes, plants, and the environment. Bridging these knowledge gaps will encourage innovation and accelerate the development of more efficient and impactful microbial products.

It is essential to encourage collaboration between researchers, industry stakeholders, policy-makers, and farmers to resolve these challenges. This collaborative effort will facilitate the exchange of knowledge and spur innovation in the field of microbial products. Increased investments in research, capacity building, and infrastructure are essential for accelerating the development of these products and driving advancements. In addition, public-private partnerships can play a crucial role in facilitating technology transfer, expanding market access, and providing regulatory support. By addressing these obstacles, we can unlock the maximum potential of microbial products and increase their adoption via sustainable agriculture. Utilizing the power of beneficial microorganisms provides numerous opportunities to improve agricultural productivity, reduce reliance on chemical additives, and promote environmentally responsible agricultural practices.

10.11 Conclusion and Future Prospects

In conclusion, the integration of microorganisms into sustainable agriculture presents promising solutions for enhancing crop productivity, soil health, and environmental sustainability. Microbes play pivotal roles as biofertilizers, biocontrol agents, and stress-tolerant enhancers, promoting eco-friendly practices and reducing reliance on synthetic inputs. Their contributions to climate-smart agriculture, microbial consortia, and biofortification of food crops underscore their significance in achieving sustainable and resilient agricultural systems. Unlocking the potential of microorganisms holds tremendous prospects for advancing and transforming sustainable crop-based food production.

Looking ahead, advanced microbial formulations offer exciting prospects for revolutionizing agricultural practices. The incorporation of nanotechnology into microbial formulations, e.g., nanobiofertilizers, can lead to improved nutrient delivery and controlled release systems, thus optimizing nutrient uptake by plants [9]. In addition, the development of encapsulated biofertilizers can protect microorganisms and ensure their viability and stability during storage and application. These formulation advances have the potential to improve the efficiency and potency of microbial products, resulting in higher plant productivity and optimized resource utilization.

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