REVIEW

Strengthening Tomato Resilience: Harnessing Microbial Consortia to Overcome Biotic and Abiotic Stress

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ABSTRACT: Tomato cultivation faces formidable challenges from both biotic and abiotic stressors, necessitating innovative and sustainable strategies to ensure crop resilience and yield stability. This comprehensive review delves into the evolving landscape of employing microbial consortia as a dynamic tool for the integrated management of biotic and abiotic stresses in tomato plants. The microbial consortium, comprising an intricate network of bacteria, fungi, and other beneficial microorganisms, plays a pivotal role in promoting plant health and bolstering defense mechanisms. Against biotic stressors, the consortium exhibits multifaceted actions, including the suppression of pathogenic organisms through antagonistic interactions and the induction of systemic resistance in tomato plants. On the abiotic front, the microbial consortium enhances nutrient availability, optimizes water retention, and ameliorates soil structure, thus mitigating the adverse effects of factors such as drought, salinity, and nutrient imbalances. This review synthesizes current research findings, highlighting the diverse mechanisms through which microbial consortia positively influence the physiological and molecular responses of tomato plants to stress. Furthermore, it explores the adaptability of microbial consortia to various agroecosystems, offering a versatile and sustainable approach to stress management. As a promising avenue for eco-friendly agriculture, the utilization of microbial consortia in tomato cultivation emerges not only as a tool for stress mitigation but also as a transformative strategy to foster long-term sustainability, reduce reliance on synthetic inputs, and enhance overall crop productivity in the face of changing environmental conditions.

KEYWORDS: Tomato cultivation; microbial consortia; biotic stress; abiotic stress; plant protection; sustainable agriculture

1 Introduction

Tomato (*Solanum lycopersicum* L.) is a globally significant crop within the *Solanaceae* family, widely appreciated for its economic and nutritional value. Tomatoes are extensively cultivated, with annual production reaching 182.3 million tons globally, making them the second most important vegetable crop after potatoes [1]. Despite this prominence, tomato cultivation faces significant challenges due to biotic and abiotic stresses, which reduce yields and compromise quality [2]. Tomato occupies a central position in

world agriculture, both economically and nutritionally. Appreciated for their many culinary applications and rich nutrients, tomatoes have become a staple in diets around the world [3]. Belonging to the *Solanaceae* family, which encompasses economically significant crops like potato, eggplant, and pepper, the tomato represents a key member of one of the most valuable plant families for vegetable and fruit cultivation [4]. The global distribution of tomato production reveals that Asia contributes 61.1%, while Europe, America, and Africa contribute 13.5%, 13.4%, and 11.8%, respectively [5]. Tomato yields exhibit significant variability across different countries. For instance, in 2022, the global average tomato yield was approximately 36.97 tonnes per hectare. In contrast, certain regions experienced notably lower yields; for example, in 2022, some areas reported average yields of only 85 tonnes per hectare, a decrease from 95 tonnes per hectare in 2021 [6]. This disparity highlights the influence of regional agricultural practices, climate conditions, and resource availability on tomato production efficiency. The primary regions for tomato consumption include China, India, North Africa, the Middle East, the US, and Brazil, with per capita consumption ranging from 61.9 to 198.9 kg [1].

Although tomatoes are generally considered a temperate crop, their cultivation extends over different climatic zones, presenting increased challenges [7]. Crop growth and productivity are often hampered by fluctuating environmental conditions and abiotic stresses. Abiotic stress factors, such as extreme water and temperature conditions, elemental toxicity, and high salinity, are the main limitations to tomato production [8,9]. Alongside these abiotic challenges, tomato plants face a series of biotic challenges that affect both yield and quality. Fungal diseases, exemplified by early blight (*Alternaria solani*) and late blight (*Phytophthora infestans*), bacterial wilt (*Ralstonia solanacearum*), and viral infections such as tomato yellow leaf curl virus (TYLCV), pose substantial threats to global tomato production [7,10]. The tomato brown rugose fruit virus (ToBRFV) has grown to be a serious worldwide danger to tomato production since its discovery in Jordan in 2015, impacting important regions such as Europe, the Middle East, North America, and Asia. It infects almost all cultivated tomato varieties, even those resistant to other tobamoviruses like Tomato mosaic virus (ToMV) [11]. These pathogens not only reduce yields but also compromise the economic viability of this crop [6].

Hence, there is an imperative requirement for a sustainable approach to managing plant stresses. A promising avenue in biological control involves the utilization of microbial consortia [12,13]. Microorganisms, including beneficial fungi and bacteria, establish intricate communities that synergistically interact to enhance plant health and resilience. Serving as biological treatments, these microbial consortia provide comprehensive protection against both biotic and abiotic stressors [14]. The complex interplay between these microbes and the natural defense mechanisms of tomato plants contributes to a holistic and sustainable strategy for managing pests and diseases [13,15,16].

In this review, we highlight the two facets of stress (biotic and abiotic) by focusing on the various challenges faced by tomato plants. It also explores the use of microbial consortia as a promising avenue for plant protection. The complex mechanisms underlying the interactions between microorganisms and tomato plants, including the secretion of bioactive compounds and the induction of systemic tolerance, will be closely examined. In addition, we discuss the practical applications of microbial consortia in the context of sustainable agriculture, with an emphasis on integrating these biocontrol strategies into integrated crop management practices.

This review employed specific keywords, including "tomato" AND "biotic stress" OR "abiotic stress" OR "drought stress" OR "salinity" OR "diseases" AND "biocontrol" OR "microbial consortium," to collect bibliometric data from the SCOPUS database (https://www.scopus.com/, accessed on 20 December 2023). The bibliometric analysis was conducted using VOSviewer processing software (v1.6.9, Leiden University, Leiden, The Netherlands). The resulting network analysis illustrated the global distribution of articles related

to the abiotic and biotic stresses of tomatoes and the application of microbial consortia as a management strategy. Fig. 1 highlights the relationship between the collected keywords and the prevailing perspectives in current research within this field of study. The spatial arrangement of nodes in Fig. 1 provides critical insights into the degree of association between keywords, countries, and research themes. Larger nodes represent terms or countries with higher scientific activity, indicating areas of significant research focus. For example, keywords such as "biotic stress" and "abiotic stress" are prominently featured, reflecting their central role in studies on tomato resilience. Similarly, countries like China, India, and the United States have larger nodes, signifying their substantial contributions to this field. The proximity between nodes reflects the strength of association or collaboration. Closely positioned nodes indicate strong thematic or collaborative links. For instance, keywords related to abiotic stresses ("drought" and "salinity") are often linked to microbial consortia studies, suggesting a concentrated effort to address these challenges through biological approaches. Colors represent clusters of related terms or regions, highlighting thematic groupings within the research landscape. For example, one cluster may focus on biotic stress management, including terms like "pathogens," "fungal diseases," and "biocontrol." Another cluster might emphasize abiotic stress mitigation, featuring terms like "drought resistance," "salinity tolerance," and "microbial interactions." The connections between nodes signify co-authorship or thematic relationships. Strong links between countries suggest active international collaborations. For example, partnerships between China and the United States are evident, reflecting joint efforts in advancing microbial solutions for tomato stress management.

(a)   (b)

Figure 1: Bibliometric and network analysis of research on the management of biotic and abiotic stresses in tomatoes. A bibliometric analysis was conducted on 1546 published articles addressing the management of biotic and abiotic stress in tomatoes. The analysis utilized the Scopus database and employed relevant keywords such as "Tomato" AND "biotic stress" OR "abiotic stress" OR "drought stress" OR "salinity" OR "diseases" AND "biocontrol" OR "microbial consortium" **(a)**. Additionally, a network analysis was performed to examine the global distribution of these articles **(b)**. In the network analysis, larger circles indicate more intense scientific activity. Colors represent groups of linked terms, with label size indicating the number of publications associated with a term. The distance between two terms reflects the degree of their association. Each node in the network represents a country, and the links between countries signify co-authorship relationships

2 Biotic and Abiotic Stresses in Tomato Cultivation

Numerous abiotic and biotic factors that are detrimental to plant development and productivity are present in crops cultivated in open fields. The current climate change, which is accelerated by rising CO_2 levels in the atmosphere [17,18], manifests itself as rising average temperatures and falling precipitation, especially in regions with a warmer climate [18]. Responses to mixtures of biotic and abiotic stressors can be influenced by the degree of abiotic stress [19]. Higher soil salt concentrations make tomatoes and other crop species more susceptible to soil-borne diseases; comparable patterns are noted when there is a water deficit [20,21]. Although research indicates that the effects on pathogenicity are often specific to particular pathosystems [22], there is a consensus that rising temperatures will lead to the geographic expansion of pathogens and increased fecundity. This, in turn, heightens the likelihood of host range expansion and the emergence of more virulent strains [22,23]. Tomato plants are particularly vulnerable to biotic stresses caused by pathogens, pests, and nematodes. Diseases such as early blight (*A. solani*), late blight (*P. infestans*), and bacterial speck (*Pseudomonas syringae pv. tomato*) pose major threats to crop productivity. Viral infections, including the TYLCV and ToMV, further exacerbate these challenges by causing stunted growth and reduced fruit quality [24,25]. Abiotic stresses, such as drought, salinity, extreme temperatures, and heavy metal toxicity, disrupt tomato physiology and limit productivity. For instance, drought reduces water uptake and photosynthesis, while salinity causes ion toxicity and nutrient imbalance. Extremes temperature adversely affect fruit setting, and heavy metals interfere with enzymatic processes, causing growth retardation [26–28]. The combination of these biotic and abiotic stresses significantly challenges tomato production, necessitating innovative and sustainable solutions to ensure stable yields and quality.

2.1 Biotic Stress

Biotic stress is considered a major threat to global food security [29,30]. Among the common pathogens affecting tomatoes, fungal diseases are a major threat. Including pathogens, pests, and nematodes, which collectively threaten the productivity and vitality of tomato plants, in addition, bacterial diseases and viral infections also contribute to biotic stress in tomato cultivation, with bacteria such as *Xanthomonas* causing bacterial spot disease and viruses such as TYLCV causing leaf yellowing and curling. Pathogens such as *A. solani*, which causes early blight, and *P. infestans*, which causes late blight, are major concerns [31]. At the same time, pests such as aphids, whiteflies, thrips, and tomato worms cause considerable damage [32]. Tomato plants are also attacked by the destructive moth *Tuta absoluta*, which damages the leaves, stems, and fruits, and it spreads quickly and is resistant to many pesticides [33]. In addition, plant-parasitic nematodes, particularly root-knot nematodes (*Meloidogyne* spp.) can compromise the plant's root system, leading to reduced nutrient uptake and stunted growth [34]. To meet these challenges, researchers and farmers are using a multi-faceted approach. This includes the development and use of tomato varieties resistant to specific pathogens and pests, the implementation of Integrated Pest Management (IPM) strategies that incorporate the pests' natural enemies, and soil management practices to mitigate the impact of nematodes [35]. Managing these pathogens is crucial to maintaining healthy tomato crops, and understanding the dynamics of their interactions is essential to developing effective strategies for mitigating biotic stress in tomato plants [2,36].

2.1.1 Fungal Diseases

Early Blight (*A. solani*): The primary disease symptom brought on by *A. solani* (Ellis & Martin) Sorauer is early blight. This disease is especially harmful to tomatoes in areas with high humidity, heavy rainfall, and relatively high temperatures (24°C–29°C). In extreme situations, it can result in total defoliation. In semiarid regions with frequent and protracted nocturnal dews, epidemics can also happen [37]. In semiarid regions

with frequent and prolonged nightly dews, epidemics can also occur, in addition to the leaf symptoms known as early blight (EB), *A. solani* can cause less economically significant symptoms on tomatoes, such as fruit rot [38] stem lesions on the adult plant, and collar rot (basal stem lesions at the seedling stage) [39]. The pathogen primarily infects leaves, stems, and fruits, leading to reduced yields and poor fruit quality [40]. Symptoms typically begin as small, dark, and irregular spots on older leaves, which expand into concentric rings resembling a "bullseye" pattern, a hallmark of the disease [37]. As the infection progresses, affected leaves yellow, wither, and drop prematurely, exposing fruits to sunscald and reducing photosynthetic capacity. On stems and fruits, dark, sunken lesions with similar concentric patterns may appear, further compromising the plant's health [38]. *A. solani* thrives under warm, humid conditions, and its spores are dispersed by wind, rain splash, or contaminated tools. The disease is exacerbated by stress factors such as nutrient deficiencies, poor drainage, or crowded planting, which increase plant susceptibility [41]. Effective management strategies include the use of resistant tomato varieties, crop rotation with non-susceptible hosts, maintaining proper spacing for air circulation, and the application of fungicides. Integrated approaches combining cultural practices and chemical controls are essential for minimizing losses caused by early blight [41].

Late Blight (*P. infestans*): *Phytophthora infestans*, an oomycete pathogen, is the source of late blight, causing leaf necrosis and fruit rot. It spreads rapidly under moist conditions and can result in total crop loss [42], a devastating disease that affects tomatoes and potatoes all over the world. In the majority of the United States and Canada, late blight outbreaks were rare before 1992 [43]. However, serious late blight outbreaks on tomatoes and potatoes were documented in the United States and Canada in 1992 and 1993 [44]. Since then, late blight has been recorded yearly. It is defined as having lesions with a distinct edge and a rough surface [43]. Tomato fruits that come into contact with the soil develop brown to black lesions at first, which grow and acquire dark zonate "buckeye" bands in the afflicted region. This pathogen infects all above-ground parts of the plant, including leaves, stems, and fruits, leading to significant yield losses if not properly managed [45]. Initial symptoms include irregular, water-soaked lesions on leaves, which rapidly enlarge, turning brown with a characteristic whitish fungal growth under humid conditions. Infected stems develop dark lesions, and fruits exhibit brown, firm rot with a leathery texture, rendering them unmarketable [46]. The pathogen's life cycle is facilitated by sporangia that disperse through water splashes or wind, germinate, and penetrate plant tissues directly or through natural openings. Under favorable conditions [46], the disease can spread rapidly, devastating entire crops within days. Effective management includes the use of resistant cultivars, proper crop rotation, and timely application of fungicides [45]. The global significance of late blight underscores the need for integrated disease management strategies to mitigate its impact on tomato production [47].

Fusarium Wilt (*Fusarium oxysporum*): Tomato wilt is one of the most significant diseases affecting tomatoes, caused by *F. oxysporum f.* sp. *lycopersici (FOL)* [48]. *FOL* infects the root epidermis, spreads through the vascular tissue, and colonizes the xylem vessels of the plant. This leads to vessel blockage and severe water stress, ultimately causing wilt-like symptoms [49]. The disease is characterized morphologically by wilted plants with yellowing leaves and little to no crop yield. Dormant chlamydospores of *FOL* can persist in infested soil indefinitely, even in the absence of a host [50]. The infection of vascular tissue by *FOL* is a complex process involving the following steps: (a) recognition of the host root through specific host-pathogen signaling, (b) attachment to root hair surfaces and hyphal propagation, (c) invasion of the root cortex and vascular tissue, followed by differentiation within xylem vessels, and (d) release of toxins and virulence factors. The colonization of xylem vessels triggers disease development, resulting in the characteristic wilting of the host plant [48]. Given the significant impact of fungal diseases on tomato production, further research into integrated management strategies, including the use of microbial consortia, is essential for ensuring sustainable crop yields [51].

2.1.2 Bacterial Diseases

Bacterial Speck (*Pseudomonas syringae pv. tomato*): This pathogen may infect *Brassica* and *Arabidopsis* species in addition to causing bacterial speck disease on tomatoes, this disease manifests as small dark spots on leaves and fruits, which can significantly reduce marketable yield, these spots, often surrounded by yellow halos, can coalesce, causing extensive leaf damage and defoliation [52]. Bacterial speck, caused by *P. syringae* pv. *tomato* (Pst), is a significant bacterial disease affecting tomato plants, especially under cool, moist conditions [53]. On fruits, lesions appear as small, raised, black specks that penetrate the epidermis, rendering the produce unmarketable. The pathogen is seed-borne and can survive in crop debris or soil, spreading through rain splashes, irrigation water, and contaminated tools [54]. Infection typically occurs via stomata or wounds, where the bacteria multiply and produce phytotoxins like coronatine, which contribute to symptom development by disrupting the plant's immune response [53]. Management strategies include using pathogen-free seeds, crop rotation, and resistant tomato varieties. Cultural practices such as avoiding overhead irrigation, proper plant spacing, and prompt removal of infected plant debris can reduce disease incidence. In severe cases, copper-based bactericides can be applied, though their efficacy is limited and may lead to resistance [55]. An integrated disease management approach is essential for effectively controlling bacterial specks and minimizing their impact on tomato production [56].

Bacterial Wilt (*R. solanacearum*): It affects the plant's vascular system, leading to wilting and eventual plant death. It is among the most damaging diseases found to date because it causes host plants to wilt quickly and fatally [57]. It has been identified as the second most significant bacterial pathogen and causes vascular wilt. The bacteria persist in soil and water, making it challenging to manage [58]. The disease is found all over the world, has a vast host range (more than 200 species), and has a detrimental economic impact [59]. Depending on the host, cultivar, temperature, soil type, cropping pattern, and strain, *R. solanacearum* can cause direct yield losses that vary greatly. The pathogen infects plants through the roots, often via wounds or natural openings, and colonizes the xylem vessels. This leads to vascular blockage, disrupting water transport and causing rapid wilting of the plant even under adequate soil moisture conditions [58]. The disease is often characterized by sudden and irreversible wilting of leaves, initially during the hottest part of the day, followed by yellowing and eventual death of the plant. A diagnostic sign is the exudation of milky bacterial ooze from cut stems or roots when immersed in water [60]. *R. solanacearum* persists in the soil for extended periods as saprophytic populations or as latent infections in alternate hosts. It thrives under warm, moist conditions, making its spread more prevalent during the rainy season [61]. The pathogen's wide host range and ability to survive in diverse environmental conditions contribute to its status as a significant agricultural problem. Despite all the effective management that involves using traditional methods or biological control agents, bacterial wilt remains challenging to control, emphasizing the importance of continued research into sustainable management practices [62]. Due to the destructive nature of bacterial diseases, an integrated strategy that incorporates resistant varieties, efficient cultural methods, and the use of biological control agents is essential for sustainable tomato production [63].

2.1.3 Viral Infections

Tomato Yellow Leaf Curl Virus (TYLCV) is spread by *Bemisia tabaci* (Homoptera: *Aleyrodidae*) and is one of the most well-known begomoviruses that infect tomatoes [64]. Tomato plants infected with TYLCV exhibit severe symptoms such as yellowing, leaf bending, and stunting, which significantly reduce tomato output, the disease's symptoms include stunting, flower abortion, a more or less noticeable upward curling of the leaflet edges, a loss in the leaflet area, and yellowing of the young leaves. Infection generally slows down plant development and yields; if an infection strikes a plant in its early stages, productivity is nearly completely lost [65]. Symptoms typically appear 10–15 days after infection, with young leaves showing

curling, distortion, and interveinal chlorosis. The virus can spread rapidly under warm and dry conditions that favor whitefly proliferation. TYLCV has a wide host range, including several solanaceous crops and weeds, which can act as reservoirs for both the virus and its vector, further complicating management efforts [64]. Effective management requires integrated strategies, including the use of resistant or tolerant tomato varieties, regular monitoring of whitefly populations, and cultural practices such as removing infected plants and using physical barriers like insect-proof nets. Biological control agents and judicious use of insecticides targeting whiteflies can also help reduce the incidence of TYLCV. Given the virus's economic impact and adaptability, ongoing research into resistant cultivars and vector management remains crucial [66].

Tomato Mosaic Virus (ToMV) is a highly contagious and economically significant pathogen of tomatoes, caused by a member of the *Tobamovirus* genus. It is transmitted mechanically through contaminated tools, hands, or infected plant debris, and occasionally via seeds, which can harbor the virus on their coat or within the embryo [67]. ToMV infects plants systemically, causing a wide range of symptoms that vary depending on the strain, environmental conditions, and host susceptibility [67,68]. Common symptoms include mottling or mosaic patterns of light and dark green on leaves, leaf distortion, and stunted growth. Infected fruits may exhibit uneven ripening, discoloration, or surface lesions, reducing their marketability [69]. The virus spreads rapidly in densely planted crops, particularly in greenhouses, where frequent handling of plants increases the risk of mechanical transmission [70]. Managing ToMV relies primarily on preventative measures, as there is no cure for infected plants. Effective strategies include using resistant tomato varieties, ensuring proper sanitation by disinfecting tools and hands, and removing infected plant debris from fields or greenhouses. Seed treatments, such as hot water or chemical disinfectants, can also reduce seed-borne transmission [71]. Crop rotation and the use of physical barriers like plastic mulches can further limit the spread of ToMV. Despite these measures, the virus remains a persistent challenge, necessitating continued research and development of resistant cultivars. Effective management of these biotic challenges is crucial for maintaining healthy tomato crops, necessitating the development of integrated and sustainable strategies. To effectively combat viral diseases in tomato crops, an integrated approach combining resistant varieties, vector control, and innovative biotechnological solutions is essential [72].

2.1.4 Pests and Nematodes

Whiteflies and Aphids: Two commercially significant pests that impact tomato production, both in protected and field settings, are obligate phloem-feeding insects called whiteflies (*B. tabaci*) and aphids (*Myzus persicae*, Homoptera: *Aphidae*) [73]. These insects' adults feed on the cell contents of afflicted plants by piercing the phloem and releasing copious amounts of honeydew, which eventually encourages the growth of sooty mold and lowers the plant's photosynthetic efficiency [74]. However, their most significant impact is as vectors for viral diseases, such as TYLCV, which can cause severe yield losses. Whiteflies excrete honeydew, a sticky substance that promotes the growth of sooty mold, further reducing photosynthesis and fruit quality [75].

Root-Knot Nematodes (*Meloidogyne* spp.): Root-knot nematodes (*Meloidogyne* spp.) are microscopic, soilborne pests that cause significant damage to tomato crops worldwide [76]. The most common species affecting tomatoes include *Meloidogyne incognita*, *M. javanica*, and *M. arenaria*. These nematodes invade the roots of tomato plants, inducing the formation of characteristic galls or knots that disrupt water and nutrient uptake [77]. Symptoms of infection include stunted growth, yellowing of leaves, wilting, and reduced fruit yield. Severe infestations can lead to plant death, particularly under water stress [78]. The life cycle begins when second-stage juveniles (J2) hatch from eggs in the soil and penetrate root tissues. They establish feeding sites called giant cells, causing abnormal cell division and enlargement [76]. The nematodes

complete their life cycle within the roots, laying eggs that are released into the soil to infect new plants [79]. The warm, moist conditions of tomato fields, especially in tropical and subtropical regions, favor their proliferation. Despite all the measures for managing, root-knot nematodes remain challenging, emphasizing the need for continued research into sustainable control methods [34]. Overall, integrated pest and nematode management strategies are crucial for minimizing crop losses and ensuring the long-term sustainability of tomato production systems. In conclusion, biotic stressors such as fungal diseases, bacterial infections, and viral pathogens pose significant threats to tomato cultivation worldwide. The complex interactions between these pathogens and environmental factors underscore the need for innovative management strategies. The next section will explore how microbial consortia can be leveraged to mitigate these biotic stresses, offering a promising avenue for sustainable crop protection.

2.2 Abiotic Stress

Abiotic stress in tomato cultivation encompasses various environmental factors that significantly impact plant physiology and productivity. High temperatures, particularly during critical growth stages like flowering and fruit set, can induce heat stress, affecting pollination and resulting in poor fruit development [80]. Conversely, exposure to low temperatures may lead to cold injury, impeding overall plant growth. As far as water stress is concerned, drought and waterlogging can have adverse effects on tomato plants, drought can lead to reduced water uptake, affecting nutrient uptake and resulting in stunted growth and reduced yield [81]. On the other hand, waterlogged soils can damage roots, depriving them of oxygen and making them more susceptible to disease [82]. Soil salinity presents another challenge, as it interferes with water and nutrient uptake, ultimately impacting plant health. Nutritional imbalances, arising from deficiencies or excesses, also contribute to abiotic stress [83]. It is essential to understand the specific nutrient requirements of tomatoes and to maintain adequate soil fertility through balanced fertilization practices [80]. Finally, light intensity plays a key role in photosynthesis and fruit development. Inadequate or excessive light can impact plant growth and yield, requiring careful management of planting density and shading practices [2]. Addressing these abiotic stress factors through innovative strategies, such as the application of microbial consortia, is crucial for enhancing tomato resilience and ensuring sustainable crop production in the face of climate change.

2.2.1 Drought

Drought is one of the main environmental stresses hampering crop production, including tomatoes. Decreased water content interferes with many plant processes and leads to reduced plant growth [84]. Therefore, studies have focused on drought. It restricts plant development and production and is a significant issue for agriculture across the world [85]. Drought stress is a major challenge for tomato plants, as it has a profound impact on their growth, physiology, and overall productivity [86]. Being highly sensitive to water availability, tomatoes undergo a series of physiological reactions when confronted with water shortage [87]. The plant's ability to absorb water is hampered, resulting in reduced water transport and nutrient uptake [84]. Stomatal closure, a common defensive mechanism, reduces water loss through transpiration but simultaneously hinders the crucial process of photosynthesis [86]. As a consequence, photosynthetic activity declines, and the plant grapples with osmotic stress, resulting in wilting and compromised cell expansion. The accumulation of reactive oxygen species (ROS) further exacerbates the challenge, causing oxidative damage to cellular structures [88]. Moreover, the effects of drought stress lead to a buildup of free radicals that affect how membranes function, proteins conform, lipids oxidize, and ultimately cause cell death [89]. Microbes that can withstand drought stress can improve plant development when there is a lack of water. To survive in low water potential, microbes have developed a tolerance mechanism through evolution, adaptation, or

both [90]. Maintaining plant water status is crucial for sustaining tolerance to drought, achieved either by limiting water loss or by increasing water absorption capacity through osmotic adjustment [91]. Developing drought-resilient tomato varieties and implementing effective water management practices, potentially enhanced by microbial consortia, are essential for ensuring sustainable production in drought-prone regions.

2.2.2 Salinity Stress

Salinity stress represents a major challenge to the optimal growth of tomato plants (Fig. 2), as it disrupts various physiological processes and has an impact on overall crop productivity, high concentrations of salts in the soil, particularly sodium chloride, disturb the osmotic balance essential for water uptake [92]. This hampers the plant's ability to absorb water, leading to water stress and subsequent difficulties in absorbing nutrients, the accumulation of sodium ions can induce ion toxicity, interfere with cellular processes, and damage cell structures [93]. Salinity stress also disrupts the balance of nutrients within the plant, competing with the uptake of essential elements such as potassium. In addition, salinity-induced osmotic stress can lead to symptoms such as leaf wilting, while excess salts can accumulate in leaf margins, causing burning and necrosis [93]. The overall consequence includes reduced photosynthetic activity, stunted growth, and lower fruit yield and quality [92]. Because of the harmful ion effects and osmotic stress caused by salinity, microbial activity is weak, which inhibits plant growth and development [94]. Under various circumstances, cations such as Na^+ (sodium), Ca^{2+} (calcium), K^+ (potassium), anions Cl (chloride), and NO_3 (nitrate) are the main contributors to soil salinity, many elements of plant life, including agricultural production, seed germination, water, and nutrient intake, as well as physicochemical and ecological balance, are adversely affected by salinity stress [95]. Moreover, it harms the nodulation process, lowering crop yield and nitrogen fixation [92]. Employing integrated strategies, including salt-tolerant varieties and microbial interventions, is essential for mitigating the impact of salinity stress on tomato yields and ensuring sustainable production in affected areas.
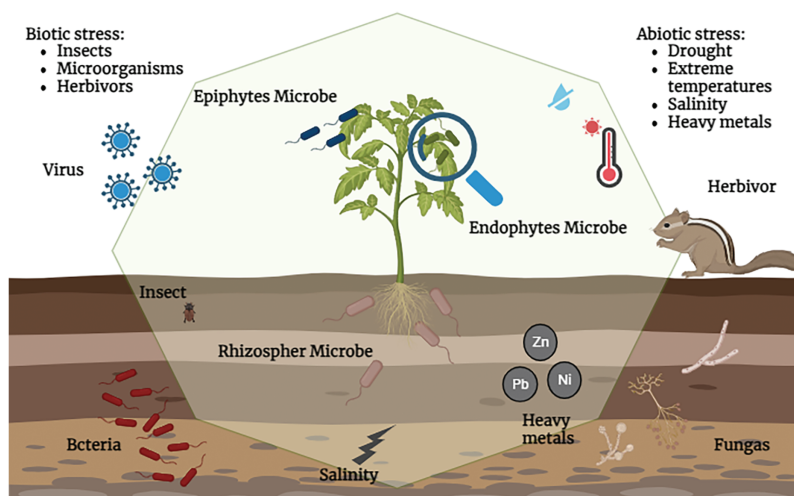

Figure 2: Tomato plant under different stresses and its association with Plant Growth Promoting Microorganisms

2.2.3 Heavy Metals

Due to their detrimental effects on crop production, human health, and the environment, heavy metal pollution of soil is one of the main issues for agricultural soils. The texture of the soil, crop productivity, growth, yield, nutrient availability, microbial community, and human health are all negatively impacted by

excessive accumulation of heavy metals in the soil [96]. On tomato plants, Cu^{2+}, Zn^{2+}, and Cd^{2+} harmful effects included decreased vegetative seedling development, flowering, and fruiting (Fig. 2) [96,97]. The lasting negative impact of these metals on the surrounding environment is attributed to their non-biodegradable nature, long biological half-life ranging from 10 to 3000 years, and their potential for accumulation in various parts of the body, metal stress decreased tomato plant height by 24.6%, 43.8%, and 58.7% at seedling, vegetative, and flowering-fruiting stages, respectively. Growth retardation, a standard physical parameter for toxicity assessment, is evident [98]. In addition to negatively affecting helpful microbiological activities, high levels of certain heavy metals in soil can reduce crop production by accumulating in various plant sections [99]. Plant enzymes and proteins with high-affinity ligands efficiently chelate heavy metals to lessen their toxicity [99]. Heavy metal interactions with plant proteins and enzymes cause a loss of bioactivity, which manifests as chlorosis, stunted development, browning of the roots, and a decrease in the activity of the photosynthetic system [100]. The presence of heavy metals in soil is also known to induce oxidative stress by producing ROS which negatively affects the two important plant physiological processes i.e., photosynthesis and respiration causing an overall reduction in plant productivity [101].

2.2.4 Temperature Stress

Temperature stress has become more frequent and intense as a result of climate change. It is well-known that heat stress can occur in tomatoes at average daily temperatures of 28°C–29°C, which are just a few degrees above the optimum temperature range of 21°C–24°C [102]. Temperature stress has a significant impact on plasma membranes, water content (transpiration), photosynthetic activity, enzyme performance, cell division, and plant development. The impact of heat stress depends strongly on the intensity, duration, and rate of temperature change. The water status of the plant is of primary importance in case of temperature change [103]. In addition, higher temperatures are often accompanied by water stress, especially in tropical and subtropical environments, temperature significantly influences various physiological processes in tomatoes, both vegetative and reproductive, independently or in conjunction with other environmental factors such as light, nutrition, and humidity [102]. High temperatures before anthesis induce critical stress, causing developmental abnormalities in the anthers, including irregularities in the epidermis and endothemis, non-opening of the stomium, and poor pollen formation [103]. Manifestations of high-temperature stress resulting in fruit set failure in tomatoes encompass a range of issues such as bud drop, undeveloped flowers, persistent flowers or calyxes, division of the antheridial cone, absence of anther dehiscence, low pollen production, pollen sterility, degeneration of the embryo sac, browning and desiccation of the stigma, reduced stigma receptivity, elongation of the style, underdeveloped ovary, poor fertilization, slow pollen tube growth, low pollen viability, low pollen germination, low ovule viability, ovule abortion, endosperm degeneration, disruption of meiosis, impaired sugar metabolism, reduced carbohydrate availability to fruit, reduced total soluble protein content, developmental abnormalities, low fruit set, reduced fruit and seed size per fruit, and inhibition of pathogen-induced resistance mechanisms [104,105].

A microbial consortium refers to a community or group of microorganisms that interact with each other in a specific environment, often collaborating to perform various functions and eventually protecting surrounding plants from biotic and abiotic stresses (Fig. 2) [106]. These communities are essential for ecosystem functioning, biogeochemical cycling, and various industrial processes [107]. The composition of a microbial consortium is quite complex and may include bacteria, archaea, fungi, and other microorganisms [106]. Their composition is influenced by factors such as environmental conditions, nutrient availability, and interspecies interactions [108]. The members of microbial consortia often work synergistically, forming intricate networks of metabolic interactions. Each microorganism within the consortium contributes to the

overall community function through its unique metabolic capabilities [109]. Developing heat- and cold-tolerant tomato varieties and implementing protective measures are crucial for ensuring stable yields and quality under challenging temperature conditions. In summary, abiotic stress factors like drought, salinity, and extreme temperatures severely impact tomato productivity. Understanding these stressors is crucial for developing effective mitigation strategies. The use of microbial consortia, discussed in the following section, presents a novel approach to enhancing plant resilience against these abiotic challenges.

3 The Toxic Effects of Pesticides on Tomatoes

The toxic effects of pesticides on tomatoes can be categorized into two main areas, which are the phytotoxic effects on the plants and health risks associated with pesticide residues [110]. Pesticides, particularly herbicides and, to a lesser extent, insecticides and fungicides, can cause significant damage to tomatoes. These phytotoxic effects include Yellowing in spots or diffuse yellowing of leaves, which can evolve into tissue necrosis. Yellowing of veins, young leaves, or the entire leaf blade, sometimes progressing to bleaching or dryness between veins [110]. Pesticide residues on tomatoes pose health risks to consumers. Studies have shown that a significant percentage of tomato samples contain pesticide residues, often exceeding maximum residue levels (MRLs) [111]. The common pesticides detected are acetamiprid, chlorpyrifos, lambda-cyhalothrin, and DDT, which are frequently found in tomato samples. Chlorpyrifos and DDT are known to be highly toxic to human health [111]. Many samples have pesticide concentrations above EU MRLs, though fewer exceed Codex Alimentarius Commission (CAC) MRLs. The exposure to these residues can lead to various health problems, including acute poisoning risks, especially if withdrawal periods are not observed [112]. Overall, while pesticides are crucial for controlling pests and increasing crop yields, their misuse can lead to both plant damage and consumer health risks. Proper application and adherence to safety guidelines are essential to minimize these effects [110].

The mechanism of action of microbial consortia in mitigating pesticide toxicity

In this regard, microbial consortia can play a crucial role in mitigating pesticide toxicity through several mechanisms, starting with the synergistic metabolic degradation where members of the bacterial consortium work together to degrade pesticides by breaking them down into less toxic or non-toxic compounds [111]. This process involves the sequential degradation of intermediate compounds produced by other members, enhancing the overall metabolic pathways for biodegradation [113]. This synergy increases the efficiency of pesticide degradation, reducing the accumulation of harmful intermediates [114]. Another mechanism is the production of biosurfactants, where Certain strains within the consortium produce biosurfactants, which increase the solubility and bioavailability of pesticides, making them more accessible for degradation. The enhanced solubility and bioavailability improve the biodegradability of pollutants [113]. There is also the self-regulation and adaptation that microbial consortia use to adapt to changing environmental conditions during degradation, ensuring optimal performance even in unstable environments. This adaptability allows consortia to maintain their degradation efficiency under various conditions. After degrading pollutants, consortia can utilize metabolites to promote the growth of other strains within the consortium [115]. This promotes a sustainable and resilient microbial community capable of continuous degradation. There are diverse degradation pathways where consortia often employ diverse bacterial species, each contributing unique enzymatic capabilities, such as oxidative and hydrolytic reactions, to degrade pesticides. This diversity ensures comprehensive degradation of a wide range of pesticides [116].

Overall, microbial consortia are generally more efficient than individual microbial strains in degrading pollutants due to their synergistic interactions [115]. They can thrive in various environmental conditions, making them suitable for different types of contaminated sites. And also, by converting toxic pesticides into

less harmful metabolites, microbial consortia help mitigate environmental and health risks associated with pesticide residues [117].

4 Microbial Consortia: Definition and Functionality

4.1 Definition and Composition

Biological Control Agents (BCAs) are a promising substitute for the misuse of agrochemicals in the management of pests and diseases [109]. Numerous soil-borne microbes coexist with plant roots; while some of them are harmful, others offer significant advantages to the host plant, such as enhanced nutrition via growth and defense against a variety of biotic and abiotic challenges [118]. It is commonly known that microorganisms can manage diseases and pests, but one of the main obstacles to their broader use in agriculture is the unpredictability of the results that are frequently observed in natural environments [119]. Research on biocontrol initially concentrated on using individual microbes [120]. Their intricate interactions with the environment and soil microbes have a significant impact on the inoculant's functionality and permanence [121–123]. Limited competitiveness against native bacteria and fluctuating environmental conditions may be the cause of single-strain inoculants' inconsistent or inadequate performance [109]. A better understanding of plant microbiota, biotic and abiotic stresses, plant genotypes, and environmental factors enables us to identify more suitable microbial candidates or inoculation strategies adapted to specific environments [123]. Depending on the locally adapted resident microbiota, edaphic factors, host genotype, root architecture, tissue-specific expression, invader density and timing of invasion events, and the bioinoculant's innate ability to get past these obstacles and establish itself in the microbiome, the bioinoculant's ability to engraft, or successfully invade a microbial community, will vary. The microbiota of plants includes a variety of species, such as bacteria, fungi, and archaea [124–128]. Plant Growth Promoting Rhizobacteria, *Trichoderma* spp., and arbuscular mycorrhiza fungi (AMF) are important contributions to biocontrol mechanisms, which protect plants either directly through microbial antagonism (antibiosis, competition, parasitism) or indirectly through plant-mediated effects (better nutrition, induced systemic resistance, ISR) [129]. For instance, the study by Rana et al. (2025) investigates the field efficacy of *Trichoderma viride*, *Pseudomonas fluorescens*, and consortia of these microbial agents against tomato late blight caused by *Phytophthora infestans*. The research likely explores how these biocontrol agents individually and in combination can manage this significant disease, which is a major threat to tomato crops worldwide. *Trichoderma viride* is known for its ability to control soil-borne pathogens, while *Pseudomonas fluorescens* is recognized for inducing systemic resistance in plants [130]. Synthetic microbial communities (SynComs) that combine fungus and bacteria can produce more robust and efficient biocontrol solutions by utilizing complementary modes of action and adjusting to a variety of environmental conditions [131]. To provide an environmentally friendly alternative to chemical pesticides in agriculture, the change in crop protection is centered on creating microbial consortia that include several beneficial bacteria and fungi with complementing biocontrol modes of action [132].

4.2 Bacterial Consortia

The application of bacterial consortia in plant protection has emerged as a promising alternative to traditional chemical pesticides, offering several advantages in terms of sustainability and disease control. Bacterial consortia, which involve the combination of multiple beneficial bacterial strains, provide enhanced protection against a broad range of plant pathogens through synergistic interactions [133]. The creation of bacterial consortia has gained interest as a sustainable method of food production since they can improve the positive properties demonstrated by these bacteria. In a synergistic or additive interaction, two or more compatible bacteria from different species may form a bacterial consortium [132,134,135]. Key components

of a microbial consortium include bacteria, which often dominate these communities and play crucial roles in nutrient cycling, organic matter decomposition, and other ecological processes [136,137]. Different bacterial species may specialize in the degradation of specific compounds or have complementary metabolic functions. Plant growth-promoting bacteria (PGPBs) such as *Bacillus, Pseudomonas, Enterobacter*, and Streptomyces are well-known members of microbial consortia, contributing to plant health and growth [32]. One of the primary benefits of bacterial consortia is their ability to combat plant diseases through various mechanisms. These include antimicrobial compound production, where bacteria produce natural antibiotics that inhibit pathogen growth, and competition for nutrients and space, which reduces the available resources for harmful microorganisms. Additionally, some bacterial consortia are known to trigger ISR in plants, enhancing their overall defense mechanisms against pathogens [138,139]. The versatility of bacterial consortia is particularly valuable in managing both soil-borne and foliar diseases, as these consortia can be tailored to target a wide range of pathogens [140]. Moreover, bacterial consortia often exhibit plant growth-promoting properties, enhancing crop yield and resilience. They can improve soil health by solubilizing nutrients, fixing nitrogen, and producing growth-promoting substances such as indole acetic acid (IAA) [141]. These benefits not only help protect crops from diseases but also support plant growth, particularly under stress conditions, thus contributing to overall agricultural productivity [142]. Research has shown that bacterial consortia can be more effective than single-strain inoculants, especially when dealing with the diversity of environmental challenges encountered in field conditions [143]. In addition to disease suppression, bacterial consortia contribute to sustainable agricultural practices [144]. By reducing reliance on chemical pesticides, which can have negative environmental impacts, these microbial solutions offer a more eco-friendly alternative [139]. Their use aligns with the principles of IPM, where multiple biological, physical, and chemical methods are combined to manage pests and diseases in an environmentally conscious manner [145]. Based on their modes of action, interactions with plants, and functions in promoting plant development and thwarting pathogens, bacterial strains employed in plant protection can be divided into several categories [146].

4.2.1 Antagonistic Bacteria

Numerous, if not all, plant species are linked to PGPB, which are frequently found in a variety of settings. The most extensively researched group of PGPB are plant growth-promoting rhizobacteria (PGPR) that colonize the rhizosphere, the closely adhering soil interface, and the root surfaces [137]. To promote plant development, PGPB can reduce environmental stress and enhance plant tolerance [147]. One of the most widely recognized groups of antagonistic bacteria are species from the genus *Bacillus*, such as *Bacillus subtilis* and *Bacillus amyloliquefaciens* [133]. The use of *Bacillus* species as biocontrol agents represents a promising and environmentally friendly alternative to chemical pesticides in agriculture [148]. These microorganisms exhibit diverse capabilities, including the production of antimicrobial compounds, promotion of plant growth, and ISR [148]. For instance, *Bacillus thuringiensis* produces Cry proteins, which are highly specific and effective against insect pests, reducing reliance on synthetic insecticides [149]. Other species, such as *B. subtilis* and *B. amyloliquefaciens*, are effective biofungicides, controlling through the production of lipopeptides, such as iturins and fengycins, which disrupt fungal cell membranes [150]. Additionally, *Bacillus* species contribute to soil health by solubilizing phosphorus and producing phytohormones like auxins and cytokinins, which enhance nutrient uptake and plant growth [151]. These multifaceted benefits position *Bacillus* as a cornerstone in sustainable agriculture, offering eco-friendly solutions for plant protection and growth stimulation while minimizing environmental and health risks associated with chemical inputs [148]. Additionally, *Pseudomonas* spp. are known for producing siderophores, which sequester iron and prevent pathogens from acquiring this critical nutrient, thereby inhibiting their growth [152]. Many PGPBs cause ISR under biotic stress, which is a physical and/or chemical alteration associated with plant defense [153].

Researchers have observed effective control of plant diseases brought on by a variety of pathogens in both greenhouse and field conditions through ISR elicited by PGPB [154]. Furthermore, induced systemic tolerance under abiotic stress has been used to characterize the physical and chemical changes caused by PGPB in plants that increase their tolerance to salt, drought, and other conditions [155]. The responses of plants to abiotic stress induced by PGPB are known as Induced Systemic Tolerance (IST) [147]. Plant biologists and microbiologists have focused a lot of their attention recently on the role of bacteria in reducing abiotic stressors on plants [156]. Many bacteria's inherent metabolic and genetic capacity aids in the tolerance of and mitigation of the detrimental effects of abiotic stressors on plants. Superoxide dismutase (SOD), catalase, and peroxidase, the primary enzymes that scavenge excessive ROS, are controlled by PGPB during the management of salt stress in plants [157,158]. Some glycine betaine-producing or osmotolerant bacteria work in concert with glycine betaine generated by plants to increase the ability of plants to withstand drought stress [159].

4.2.2 Plant Growth-Promoting Rhizobacteria (PGPR)

PGPR are beneficial rhizospheric bacteria that enhance plant growth and suppress diseases in crops. The term "PGPR" was introduced by Kloepper and Schroth in 1978 to describe microbes that promote plant development by colonizing roots effectively [160]. These bacteria play a crucial role in agricultural sustainability by improving growth parameters and providing biological disease control. The rhizosphere supports the formation, development, and operation of a variety of microbial communities, including PGPRs [132]. It provides plants with protection against phytoparasites [161] while enhancing their tolerance to abiotic stresses [162]. PGPR modulates auxin/cytokinin ratios and stimulates phytohormonal signaling for plant defense. Plants also recruit beneficial microorganisms to the rhizosphere when facing pathogens [132]. PGPR offers plants both direct and indirect protection against pests and diseases. Species like *Bacillus*, *Pseudomonas*, *Rhizobium*, *Azotobacter*, *Enterobacter*, and *Azospirillum* have been shown to improve plant health through various mechanisms. These include the production of plant hormones such as ethylene, indole-3-acetic acid (IAA), cytokinins, and gibberellic acid, which promote growth by enhancing root development and nutrient and water uptake [132]. Additionally, PGPR can fix nitrogen, enriching soil fertility. Indirectly, they protect plants by producing antimicrobial compounds, including antibiotics and siderophores, which suppress harmful phytopathogens [163]. However, while PGPR have demonstrated success in controlled environments, their effectiveness often diminishes in field conditions due to unstable interactions with host plants, influenced by environmental factors such as soil pH, moisture, and temperature [133]. Moreover, for PGPR to be widely adopted, it is crucial to integrate them into sustainable agricultural practices, combining them with crop management techniques and cultural practices to maximize their effectiveness. PGPR can become a cornerstone of sustainable agriculture, reducing reliance on chemical pesticides and fostering healthier crop ecosystems [123,164].

4.3 Fungal Consortia

Due to their effectiveness in managing plant diseases and infections, fungus antagonists are now being extensively researched and used as BCAs. Fungal consortia, which combine diverse fungal species with complementary traits, have emerged as a sustainable tool in modern agriculture. These consortia utilize the unique abilities of different fungi to simultaneously enhance plant growth, improve soil health, and suppress pathogens and pests [165]. Mycorrhizal fungi, such as *Rhizophagus irregularis*, contribute to better nutrient acquisition and increased plant resilience, while entomopathogenic fungi like *Beauveria bassiana* and *Metarhizium robertsii* target pest populations. The synergy between these fungi amplifies their individual effects, making fungal consortia a cornerstone of IPM strategies. Their ability to integrate pest control

with soil fertility management makes them vital in sustainable crop production [166]. Remarkably, fungal inoculants, including all tested mycorrhizal strains, *Trichoderma harzianum*, the EPF (Entomopathogenic Fungi) *Metarhizium robertsii*, and the M2 SynCom (a fungal consortium composed of *B. bassiana*, *M. robertsii*, and *R. irregularis*), achieved significant reductions in the natural incidence of *Tuta absoluta*, a major pest in tomato crops [33]. *R. irregularis* and *M. robertsii* demonstrated exceptional effectiveness, reducing pest incidence by up to 90%. These findings highlight the potential of fungal consortia to enhance plant defenses and effectively protect crops from pests [33]. The dual role of fungal consortia in promoting plant health and directly suppressing pests showcases their importance in reducing reliance on chemical pesticides. Their integration into IPM practices offers a holistic approach to crop management, addressing both productivity and environmental sustainability [167]. Synergistic formulations, such as the M2 SynCom, underscore the advantages of combining multiple fungi, ensuring consistent performance across diverse agricultural conditions. These results reinforce the transformative role of fungal consortia in advancing sustainable agriculture and safeguarding essential crops [168].

4.4 Mechanisms of Action

4.4.1 Antibiosis

Antibiosis is a crucial biological control system for protecting plants, wherein helpful microbes like fungi and bacteria create antimicrobial chemicals that stop plant diseases from growing [169]. These substances, which include volatile organic compounds (VOCs), antifungal proteins, and antibiotics, can directly inhibit the growth of pathogenic microorganisms by interfering with their biological functions or outcompeting them for resources [170]. For instance, *Trichoderma* spp. release enzymes like chitinases to break down fungal cell walls, while *Bacillus* spp. and *Pseudomonas fluorescens* generate antibiotics that target pathogens like *Fusarium* and *Pythium* (Table 1) [171]. In addition to assisting in the management of plant diseases, this mechanism lessens the demand for chemical pesticides, providing a more environmentally responsible and sustainable option for agricultural pest control [172].

The application of a microbial consortium, comprising effective strains for biological control, represents an effective strategy compared to the use of individual microbes for tomato plant disease management [140]. In addition, the application of microbes in a consortium can improve the efficacy, reliability, and consistency of microbes under various soil and environmental conditions [136]. One fundamental mechanism involves the suppression of plant pathogens through competitive exclusion, where beneficial microbes outcompete harmful pathogens for essential resources [121]. Additionally, certain members of the microbial consortium produce antimicrobial compounds, such as antibiotics and lytic enzymes, directly inhibiting the growth of plant pathogens [155]. Another crucial aspect is the ISR in plants, wherein the presence of specific microbial species triggers the plant's immune response, fortifying it against future infections [12]. Nitrogen-fixing bacteria within the consortium contribute to nutrient availability, promoting plant growth [121]. Moreover, microbial communities enhance soil structure, water retention, and nutrient cycling, fostering a conducive environment for plant development [136]. These complex interactions within the microbial consortium exemplify nature's ingenious strategy to bolster plant defenses and sustain agricultural ecosystems [152]. PGPB may modify plant gene expression to make the plant less susceptible to these stressors, even while they can offer some protection against the inhibitory effects of salt or drought stress [173]. For instance, it has been demonstrated that different PGPB promote plant production of the metabolites betaine, proline, and trehalose as well as the creation of enzymes like superoxide dismutase (SOD) and catalase (CAT) that may detoxify reactive oxygen species [174] (Table 1). Among these antagonistic microorganisms, which exert various mechanisms to combat the disease, namely inhibition of the pathogen by antimicrobial compounds (antibiosis), competition for iron through the production of siderophores;

competition for colonization sites and nutrients supplied by seeds and roots; induction of plant resistance mechanisms, inactivation of pathogen germination factors present in seed or root exudates, or degradation of pathogenicity factors of the pathogens such as toxins and parasitism, which may involve the production of extracellular cell-wall-degrading enzymes such as chitinase and b-1,3 glucanase, which degrades the cell walls of pathogens [12,173,175]. Antibiotic production by bacteria, particularly *Pseudomonads*, appears to be tightly regulated by a two-component system involving an environmental sensor and a cytoplasmic response factor [173]. Using PAO1 mutants of *Pseudomonas aeruginosa* unable to produce hydrogen cyanide (HCN), it has been confirmed that cyanide poisoning is responsible for the death of the nematode *Caenorhabditis elegans* [176]. *Pseudomonas* species can synthesize enzymes that can also modulate plant hormone levels and limit available iron through the production of siderophores. In addition to killing the pathogen by producing antibiotics [177].

4.4.2 Induced Systemic Resistance (ISR)

Beneficial microorganisms, such as microbial consortia, can trigger the plant defense mechanism known as ISR (Fig. 3), which provides broad-spectrum resistance against a variety of diseases [178]. By producing elicitors like lipopeptides, siderophores, and volatile organic substances, microbial consortia, which are made up of synergistic mixtures of bacterial and fungal strains, improve ISR [179]. These elicitors cause the overexpression of genes linked to defense by initiating signaling pathways in plants, which mainly involve ethylene (ET) and jasmonic acid (JA). ISR offers a broader response against biotic stressors than systemic acquired resistance (SAR), which is pathogen-specific and reliant on salicylic acid (SA) [180]. For example, it has been demonstrated that consortia of *Bacillus*, *Pseudomonas*, and *Trichoderma* species can cause ISR by promoting the accumulation of phenolic substances (Table 1), secondary metabolites, and defense enzymes such as polyphenol oxidases and peroxidases [178]. Because systemic priming increases plant resistance to pathogen assault without causing growth penalties, ISR is a sustainable and environmentally beneficial crop protection method [181]. Further highlighting their function in integrated pest management (IPM) systems, studies have shown how effective microbial consortia are at activating ISR to fight diseases like bacterial specks, *Rhizoctonia* root rot, and *Fusarium* wilt in tomatoes [179]. Inducing systemic resistance through the application of microbial consortia offers a sustainable approach to enhancing tomato resistance against a broad spectrum of pathogens and pests, reducing the need for chemical interventions.
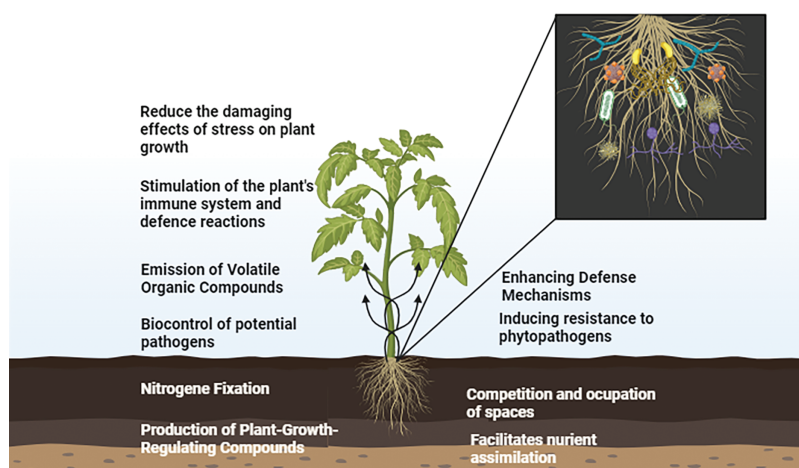

Figure 3: Diverse effects of microbial consortia on plant growth and health

4.4.3 Nutrient Solubilization and Cycling

Microorganisms play a pivotal role in nutrient solubilization and cycling (Fig. 3), which significantly enhances soil fertility and plant nutrient uptake [182]. Nitrogen fixation is a critical process performed by bacteria such as *Azospirillum*, which convert atmospheric nitrogen into bioavailable forms, ensuring an essential supply for plant growth [183]. Additionally, phosphorus, often present in insoluble forms in soil, is solubilized by beneficial microorganisms that produce organic acids, such as gluconic and citric acids [184]. These acids dissolve insoluble phosphate compounds, making phosphorus readily available for plant uptake [137]. The dual role of these microbes in nitrogen fixation and phosphorus solubilization underscores their importance in sustainable agriculture by reducing dependency on chemical fertilizers while maintaining soil health [185]. Enhancing nutrient uptake through the application of microbial consortia represents a sustainable strategy for improving tomato growth and productivity, particularly in nutrient-poor soils.

4.4.4 Stress Mitigation

Through a variety of processes, microbial inoculants such as endophytic fungi and PGPR improve plant tolerance [181]. They generate phytohormones that regulate plant development and stress response, such as gibberellins and indole-3-acetic acid (IAA) [186]. Furthermore, by fixing atmospheric nitrogen and solubilizing phosphorus, these microbes enhance nutrient absorption and increase plant vigor under stress [187]. Beneficial microorganisms encourage the buildup of osmoprotectants such as proline, glycine betaine, and trehalose under salt and drought stress. These substances assist preserve cellular osmotic equilibrium and shield macromolecules from harm [188]. Additionally, these bacteria increase the activity of stress-related enzymes that detoxify ROS and stop oxidative damage brought on by environmental stressors, such as peroxidase, catalase, and superoxide dismutase (SOD) [156,189]. Under water-deficient situations, the formation of exopolysaccharides by specific bacteria also helps to improve soil structure and water retention, creating a more suitable environment for root development [190]. By lowering dependency on chemical inputs and increasing crop yield and sustainability, the incorporation of microbial solutions into agricultural methods presents a viable and environmentally responsible method of managing abiotic stress [191] (Table 1).

Table 1: Antagonists and their effects on tomato pathogens

Antagonist	Effect	Pathogen	Diseases	Reference
Paenibacillus spp.	Nitrogenase activities, antibacterial capacities, biofertilizer, biocontrol agent, and inducing systemic resistance against diseases, decreasing environmental stresses	*Alternaria longipes*	Alternaria rot	[192]
Pseudomonas putida		*Clavibacter michiganenensis*	Bacterial canker	[193]
P. chlororaphis		*Fusarium oxysporum*	Root rot	[194]
Aspergillus tubingensis		*Fusarium solani*	Root rot	[195]

(Continued)

Table 1 (continued)

Antagonist	Effect	Pathogen	Diseases	Reference
Trichoderma harzianum				[196]
Streptomyces sp.				[197]
Candida oleophila		*Botrytis cinerea*	Grey mold	[198]
Paenibacillus polymyxa				[199]
Micromonospora				[200]
Pantoea eucalypti				[201]
Trichoderma	Plant protection	*Phytophthora infestans*	Tomato late blight	[177]
Bacillus subtilis		*Phytophthora* spp.	Collar rot	[202]
		Pythium spp. *Fusarium* spp. *Rhizoctonia* spp.	Root rot	
Bacillus pumilus		*Rhizoctonia solani*	Damping-off seedlings	
Bacillus cereus				
Bacillus amyloliquefaciens		*Pythium* spp. *Rhizoctonia solani*	Root rot Damping-off seedlings	

The mechanisms of action of microbial consortia in enhancing tomato resilience are complex and multifaceted, involving a combination of direct and indirect effects on plant physiology and defense responses. Further research is needed to fully elucidate these mechanisms and optimize the application of microbial consortia in tomato cultivation.

5 Applications in Plant Protection

5.1 Mitigation of Biotic Stress

To combat biotic stress, these consortia, which are made up of helpful bacteria, fungus, and other microorganisms, use two different strategies. First, by producing antimicrobial substances such as lipopeptides, antibiotics, and volatile chemical compounds, they directly inhibit infections. For instance, *Bacillus* species create lipopeptides called iturins and fengycins that break down the cell membranes of fungi, whereas

antibiotics stop bacteria from growing [150]. Second, microbial consortia augment the plant's innate immune system and induce systemic resistance (ISR), which improves plant defenses. Defense-related enzymes like peroxidase and polyphenol oxidase are produced as a result of signaling pathways being activated by the creation of elicitors such as surfactins and jasmonates. These enzymes reduce oxidative stress-induced damage and aid in the fight against invasive infections [167,203]. Furthermore, by increasing nutrient availability and generating phytohormones that boost general resistance to biotic stress, microbial consortia support plant health [151]. They are an essential part of sustainable agriculture since they may supplement or replace chemical pesticides, lowering pollution levels while preserving crop yield and health [148]. The utilization of microbial consortia represents a promising strategy for managing biotic stresses in tomato plants, offering a sustainable alternative to conventional chemical approaches [204].

5.2 Enhancing Resistance to Abiotic Stress

Abiotic stresses are major constraints of plant growth and development, which in turn affects crop yield, food quality, and global food security. Drought, salt, and heavy metal stress, as well as nutrition and temperature stress, are the major ones to be known. Drought is one of the most significant ones, followed by salt stress [205]. These two stresses have a maximum deleterious effect on extensive areas of land [206]. Under stress conditions, various parameters such as molecular biology, biochemistry, and physiology of plants are affected. Drought and salt stress are known to disrupt photosynthesis, leading to leaf senescence, excessive formation of ROS, nutritional deficiencies, and the breakdown of cellular organelles and metabolism, all of which contribute to reduced plant growth [14]. The resultant damage comprises both physiological and metabolically disrupted homeostasis of plants [205,206]. Another significant soil stressor is metal stress, which is getting worse due to a variety of human-caused reasons. The unchecked population growth and industrial revolution are causing organic wastes and toxic metals to accumulate in the soil, rendering it unsuitable for agricultural practices and harmful to all living organisms [207]. In this regard, the use of inorganic fertilizers and chemical pesticides degrades soil fertility and pollutes the ecosystem. Certain exudates released by the plant during the stress phase can serve as a signaling mechanism to change or establish a healthy rhizosphere soil community [208,209].

PGPB are a sustainable alternative for improving plant growth and soil fertility. They regulate crop growth, development, and productivity by improving the availability and biosynthesis of limiting macro- and micronutrients. Plant growth-promoting microorganisms (PGPMs), including bacteria, actinomycetes, fungi, and algae, have beneficial effects on plant growth through direct or indirect mechanisms. They play a significant role in sustainable agriculture by increasing crop production, improving soil fertility, promoting diversity, inhibiting pathogen growth, and maintaining system sustainability [12,209]. In the same context, applying microbial consortia to agricultural fields is a novel natural method that can improve plant development and help plants resist a variety of stressors since compost is composed of a variety of microbial consortia that can operate in a range of temperature variations [210].

Compared to bacteria, fungi are more susceptible to greater salt concentrations [211]. Their mechanisms and modes of operation differ. These processes result in an increase in root length, surface area, and root count, which facilitates nutrient absorption [212]. The main indirect process is a decrease in the incidence of plant pathogens that cause illness [213]. Rhizobacteria that colonize roots generate ACC (1-aminocyclopropane-1-carboxylate) deaminase, which breaks down ACC into ammonia and α-ketobutyrate while reducing ethylene [214]. The enzyme Rhizobitoxine increases nodulation and inhibits ethylene synthesis under stressful situations [215]. By possibly collecting osmolytes in their cytoplasm, which counteract osmotic stress and preserve cell turgor and plant development, plant growth-promoting bacteria

(PGPB) may be able to reduce the effects of salt stress [211]. For plants and microorganisms, low and high osmotic potential make it difficult for them to absorb water from the soil [213].

5.2.1 Enhancing Drought Resilience in Plants

Low soil moisture or water content that is insufficient to meet plant needs is known as drought stress. Water deficit or stress is produced when a plant's water content drops to the point that it interferes with regular plant functions or when water loss from metabolic processes and transpiration surpasses the amount of water available for absorption [14]. Reduced soil moisture brought on by decreased rainfall or additional irrigation may potentially be the cause. Numerous plant stages and metabolic systems have been revealed to be negatively impacted by water stress [216]. For instance, water stress lowers a plant cell's water potential, which raises the concentration of solutes. This further prevents cell expansion, stem proliferation, and root elongation, all of which limit plant development [217]. But in stressful situations, rhizobacteria may be able to proliferate and help plants adapt to more stressful situations [218] even more PGPR changes the structure of the roots and increases the plant's capacity to absorb nutrients and draw water [208,219]. ACC deaminase activity, production of exopolysaccharide (EPS) [220] and volatile organic compounds (VOCs), osmolyte and antioxidant production, enhanced mineral nutrient uptake, phytohormone production, and modulation are among the mechanisms proposed by PGPM to overcome drought stress in plants [207]. Additionally, through the production of osmoprotectants like proline and betaine, which stabilize cell structures, microbial consortia assist plants in maintaining water balance during dry circumstances [221]. For example, fungi such as *R. irregularis* work symbiotically with plant roots to enhance water absorption [222]. Through these pathways, the PGPRs are given to plants, either individually or in combination, to alleviate drought stress [223]. By improving physiological parameters like shoot length, root length, and fresh and dry weight of root and shoot, as well as by regulating defense enzymes like superoxide dismutase, catalase, and lipid peroxidase, microbial consortia of *Pseudomonas putida* NBRIRA + *B. amyloliquefaciens* NBRISN13 reduce drought stress in chickpeas. They also increase soil enzyme activity and microbial diversity in the rhizosphere area under drought stress [224].

5.2.2 Enhancing Salinity Stress Resilience in Plants

A salt concentration that is more than what plants need is referred to as soil salinity. The soil around the root zone turns saline when the electrical conductivity (EC) approaches 4 dS/m (40 mM NaCl) [225]. In addition to affecting the physicochemical characteristics of soil and interfering with nutrient absorption, excessive salt concentrations that result in limited water availability also produce drought-like conditions and make nutrients inaccessible to plants [14]. Plant growth, photosynthetic ability, CO_2 absorption, and nitrogen content are all impacted by salt stress, which also causes ion toxicity and oxidative stress [226]. However, under salty conditions, the combination of distinct but compatible genera of microorganisms can significantly increase plant development and may help to mitigate salinity [227]. Under salinity, microbial consortia perform several vital functions, such as enhancing plant development, serving as osmoprotectants, antioxidants, and biocontrol agents, and lowering soil stress. For more details, the enzyme ACC deaminase, which is produced by bacteria in consortia, decreases ethylene levels in plants, increasing their ability to resist salt. Additionally, they release organic acids that decrease ion toxicity [213] (Fig. 4).

The interaction of halotolerant bacteria such as *Enterobacter cloacae* and *Bacillus drentensis* improved the growth of salt-stressed mung beans by enhancing water uptake and nutrient availability. These bacteria contribute to soil health through mechanisms like exopolysaccharide production, which helps retain moisture and nutrients [228]. One of the applications on tomato plant was the study of Kapadia C et al. who demonstrated that four rhizobacteria strains in microbial consortia *Bacillus* sp., *Delftia* sp., *Enterobacter*

sp., and *Achromobacter* sp. can assist tomatoes in overcoming the effects of salt stress [229]. By improving plant development indicators, chlorophyll content, mineral absorption, accumulation, and translocation to a new region of the plant, consortiums help tomatoes that are under salt stress [227]. Other research on wheat, indicated that multi-strain bacterial consortia could effectively promote wheat growth under salinity stress. The co-inoculation of different PGPR strains was more beneficial than single-strain applications, as it harnessed a broader range of growth-promoting traits. This approach has shown promise in enhancing plant resilience to salinity, particularly in arid regions [230].
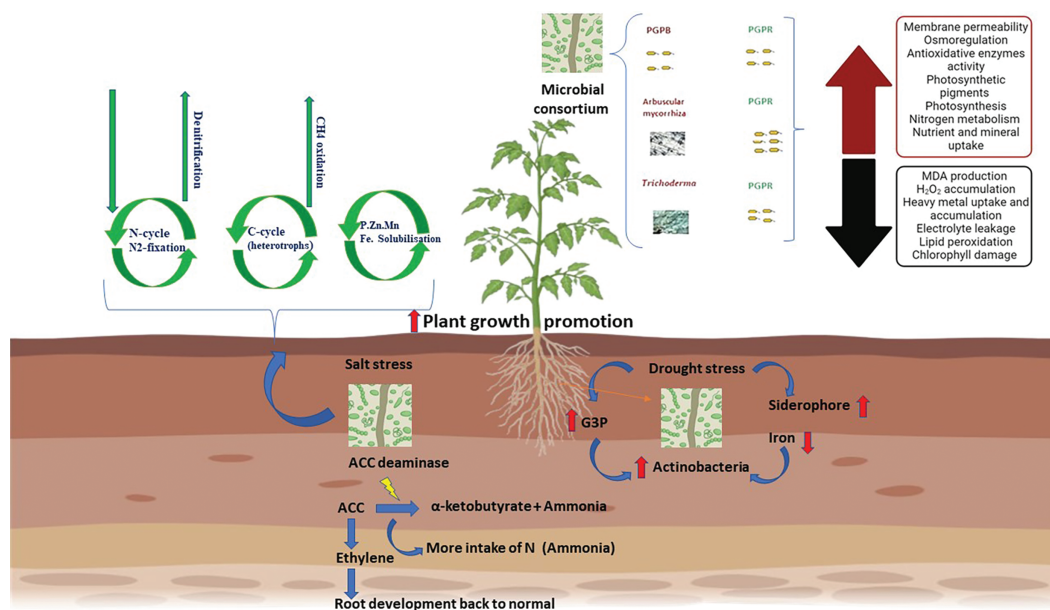
Figure 4: Mechanisms and role of microbial consortia to enhance resistance against abiotic factors

5.2.3 Heavy Metal Detoxification

Heavy metals (HMs) are defined as elements with metallic properties and a broad molecular weight range, including transition metals, which can be bioaccumulated easily in affected soils. Even more, they have increased significantly in soil due to the Industrial Revolution and human activities [231]. Excessive metals in soil hinder soil characteristics and fertility, making it unsuitable for agricultural purposes [207]. Plant metabolism and growth are also harmed by the abundant HM in soil, which is absorbed and translocated to numerous organs of plants [207].

In the soil, microorganisms have the potential to bind and sequester heavy metals, lowering their availability to plants. This enhances plant development and reduces oxidative stress. They also assist in the phytoremediation of polluted locations because of well-known plant growth-enhancing processes such as siderophore synthesis, nitrogen fixation, phosphate solubilization, and hormone secretion (IAA, GA) [232]. These types of PGPR are known as heavy metal-resistant bacteria in the rhizosphere and they have a major impact on plant tolerance and accumulation. Rhizobacteria that were isolated from mining and mining sites can resist perfectly the effects of heavy metal stress [233]. The mechanism behind it is the increasing dehydrogenase activity that reduces metal accumulation in plant parts and soil and controls the bioaccumulation factor (BAF) of heavy metals. The rhizobacteria consortia of *Bacillus cereus* MG257494.1, *Alcaligenes faecalis* MG966440.1, and *Alcaligenes faecalis* MG257493.1 demonstrated this type of mechanism

of tolerance against heavy metals (Cu, Pb, Cd, and Zn) [14,234]. A study conducted in São Paulo, Brazil, utilized a heavy-metal resistant bacterial consortium derived from a contaminated river to design a fixed-bed bioreactor for copper removal. The consortium demonstrated a copper sorption capacity of 450 mg/g dry cells. In a controlled setup, the biofilm formed on granular activated carbon (GAC) retained 45% of the copper mass in the influent, significantly outperforming a control column with only GAC, which retained 17% [235], In another study, *Bacillus marisflavi* and *Trichoderma longibrachiatum*, two microbial strains, showed moderate tolerance to metals. Electrochemical screen-printed electrodes were used to determine metal concentrations before and after bioremediation. *T. longibrachiatum* showed higher bioremediation potential, removing 87% of Cr and 67% of Zn, while *B. marisflavi* removed 86% of Pb [236].

5.3 Application Methods

Microbial consortia, which are communities of two or more microbial species that interact symbiotically, have diverse applications in agriculture and environmental management [237]. Their use in seed treatments, root inoculants, and foliar sprays is gaining traction due to their ability to enhance plant growth, improve soil health, and facilitate the degradation of complex organic materials [133].

5.3.1 Seed Treatments

Coating seeds with microbial consortia promotes early colonization of the rhizosphere, increasing root health and early-stage resistance [238]. These treatments can enhance nutrient absorption and protect against disease. For example, specific microbial combinations have been demonstrated to improve the degeneration of paddy straw residues when employed with seeds, enabling better crop establishment and decreasing disease incidence. This strategy not only improves seedling performance but also adds to sustainable farming practices by reducing the demand for chemical pesticides and fertilizers [239].

The study conducted by Raja et al. (2019) used liquid microbial cultures to enhance germination and vigor in pigeonpea seeds [240]. The bacterial strains used were *Methylobacterium, Rhizobium*, and phosphobacteria, which were cultured in specific broths. After application, seeds were assessed for viability and vigor. The study also investigated the compatibility of microbial cultures with seed-treating chemicals. The results showed that pink pigmented facultative methylotroph (PPFM) performed the best in enhancing seed germination and vigor, particularly at a 1:100 dilution for 3 h. The use of microbial consortia improved germination and vigor. However, chemical treatments like carbendazim reduced microbial populations, but polymer coating mitigated this effect. The study concluded that liquid microbial cultures can effectively enhance seed germination and vigor in pigeonpea, provided the concentration and soaking duration are carefully managed [240]. Raza et al. (2024) used a synthetic consortium of beneficial *Bacillus* microbes to manage Fusarium wilt disease and improve seedling growth in pea seeds. The strains were *B. subtilis*, *B. amyloliquefaciens*, and *Bacillus fortis*, identified through 16S rRNA gene sequencing. They were combined into a seed coating consortium, which was prepared by preparing an aqueous suspension of the bacterial consortium [241]. The seeds were then coated with the consortium using gum arabica as a binding agent and talc as a filler material. The seeds were then wetted with the bacterial suspension, dried, and stored for future use. The study evaluated the performance of coated seeds in sterilized potting mix, revealing that they had higher germination rates, seedling length, and biomass compared to untreated seeds. When challenged with Fusarium wilt, coated seeds reduced disease index and improved growth. The coating also increased phenolic compounds and defense-related enzymes, enhancing disease resistance. This suggests that seed coating with beneficial *Bacillus* bacteria is effective for managing Fusarium wilt [241]. Sharma et al. (2003) experimented comparison between a cyanobacteria consortium (BF1-4) and a biofilm (AnTr biofilm) on maize inbreds (HKI323PV and HKI161PV). The cyanobacterial consortium included *Anabaena torulosa*

(BF1), *Nostoc carneum* (BF2), *Nostoc piscinale* (BF3), and *Anabaena doliolum* (BF4). The study found that seed inoculation with microorganisms increased germination percentage and enzyme activities for both maize inbreds [242]. The highest germination values were found for HKI323PV seeds inoculated with An-Tr biofilm, while the greatest increases were found for HKI161PV. This improved mobilization of nutrients at the seed stage provided energy for seedling growth, with significant increases in root length, shoot length, fresh weight, and dry weight [243].

Mastouri (2010) investigated various abiotic stress conditions during tomato seed germination and assessed the efficacy of *Trichoderma* seed therapy as a way of maintaining high seedling performance even under such settings [244]. *Trichoderma* treatment had no impact in the absence of stress, but under osmotic, salt, or suboptimal temperature circumstances, it ensured a quicker and more uniform germination in comparison to the control. *Trichoderma* may provide physiological protection in stressed seedlings by reducing the buildup of lipid peroxides in the presence of oxidative damage [245]. Another coating inoculum composed of *P. fluorescens* and *T. harzianum* either in combination or singly induced a lower mean germination time (less than 2.5 days) of tomato seeds and a significantly higher germination rate (more than 48%); the combinations of inoculants were more effective than single-isolate treatments [246].

5.3.2 Root Inoculation

Applying consortia directly to the root zone enhances nutrient uptake, soil health, and long-term protection against stressors [247]. Root inoculants include the direct application of microbial consortia to plant root zones. These consortia can improve nutrient availability, notably nitrogen and phosphorus, while also improving soil structure through enhanced microbial activity. Studies have shown that microbial inoculants including strains such as *Bacillus* and *Pseudomonas* may greatly boost root development and nutrient absorption in diverse crops [239,248]. Furthermore, these inoculants may help in the bioremediation of polluted soils by degrading contaminants via the metabolic activities of the bacteria involved [248].

A study designed microbial consortia including *B. amyloliquefaciens*, *Pseudomonas azotoformans*, and *T. harzianum* to control root and shoot pathogens like *F. oxysporum* and *Botrytis cinerea*. The microorganisms were prepared and cultured in specific media, and their spores or cells were collected, washed, and resuspended in sterile water. The microbial suspensions were then applied to the seeds or roots of tomato plants (Fig. 5). Surface-sterilized tomato seeds were treated with microbial suspensions, and the seeds were sown in pre-infected soil to simulate a disease-prone environment. The microbial treatments were applied by pipetting the suspension onto the seeds and covering them with sterile vermiculite. The effectiveness of the treatments was evaluated by measuring plant survival rates and disease suppression after 15 days. The study also explored the root colonization of the applied microorganisms, quantifying colonization using colony-forming unit (cfu) counts after 15 days of growth. *T. harzianum* and the microbial consortia showed the highest efficacy in increasing plant survival and reducing disease symptoms [133].

Another study investigated the effects of microbial consortia, *B. amyloliquefaciens*, and AMF + *Pseudomonas brassicacearum* on drought protection across various crops. The results indicated that specific combinations of fungal and bacterial inoculants significantly improved vegetative growth under drought conditions, showcasing the potential of microbial consortia to enhance resilience against abiotic stress [249]. This synergistic interaction enhances nutrient uptake and overall plant health when used as a root inoculant. It is also observed in other studies like the one made by Cirillo et al. (2023) which used the combination of *Trichoderma* strains with beneficial microorganisms such as *Azotobacter* and it has shown to improve tomato plant performance under varying environmental conditions [250]. Soil amendment with microbial consortia represents a sustainable strategy for improving soil health, enhancing nutrient availability, and promoting tomato growth and productivity.
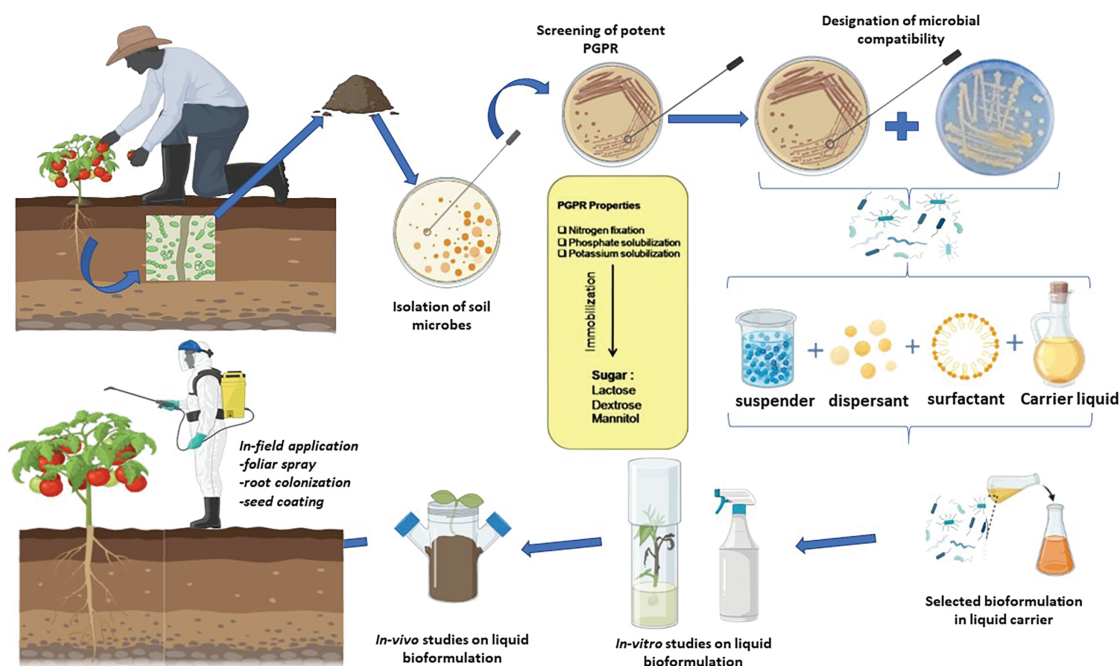
Figure 5: Preparation of microbial consortium and practical applications in plants and soil health

5.3.3 Foliar Sprays

Spraying microbial formulations on the leaves can lower the occurrence of foliar diseases and pests, work as a barrier of protection [133]. Foliar applications of microbial consortia offer helpful microorganisms straight to plant leaves. This method can help plants resist biotic pressures (such as pests and diseases) and abiotic difficulties (such as drought). For example, microbial sprays have been used to promote the suppression of organic wastes *in-situ*, allowing for greater nutrient cycling within the ecosystem [239]. The use of such sprays has been found to boost crop health and production while supporting sustainable agriculture practices. Sprayed directly onto tomato leaves, this consortium colonized foliar tissues and persisted for up to 4 weeks post-application. Upregulated defense genes (PR-1a, LoxD, GluB) linked to salicylic acid, jasmonic acid, and ethylene signaling pathways [133]. *Trichoderma* spp. degraded fungal cell walls via chitinases, while *Bacillus* and *Pseudomonas* spp. produced antimicrobial compounds (lipopeptides) and competitively excluded pathogens through biofilm formation [251]. Effectively controlled both foliar *Botrytis cinerea* (gray mold) and root *Fusarium oxysporum*, matching the efficacy of the best-performing individual strains [133]. Fusarium wilt diseases significantly impact crop growth and productivity. A consortium of antagonistic rhizospheric *Bacillus* strains and quercetin was evaluated as a potential remedy for managing tomato plant Fusarium wilt. The combination of *Bacillus* strains and quercetin reduced the disease index by 69% and increased plant growth attributes. The treatment also improved total phenolic contents and enzyme activities of the phenylpropanoid pathway enzymes. Non-targeted metabolomics analysis showed that the *Bacillus* consortium and quercetin effectively ameliorated the production of different metabolites in tomato plants [251]. Sidharthan et al. developed a microbial-based consortium to combat Fusarium wilt in tomatoes. The consortium, consisting of *Chaetomium globosum, Pseudomonas putida, Bacillus subtilis*, and *Trichoderma harzianum*, showed positive interactions in growth, antagonism, and gene expression. The combination was found to be most effective, reducing Fusarium wilt incidence by 71% and increasing plant growth by 135%. The consortium's effectiveness is partly due to the upregulation of defense-related genes in

tomato plants, suggesting a plant-mediated response. The consortium's effectiveness was primarily applied via seed treatment and soil drenching, suggesting adaptability to foliar use [252]. Foliar spray application of microbial consortia offers a direct and effective approach for enhancing plant defense responses, mitigating stress, and improving overall tomato health. Optimizing application strategies for microbial consortia is crucial for maximizing their beneficial effects on tomato plants and ensuring their effective integration into sustainable crop management systems.

6 Promoting Soil Health

Apparently, within a plant environment and regarding its location, the microbial agents within a plant microbiome participate in tasks that are complicated in which they can coexist and communicate under so many environmental conditions [253,254]. Accordingly, when abiotic and biotic agents are presented in soil, they may negatively impact the beneficial properties of individual microbial strains, such as their disease-inhibiting and pollutant-eradicating effects, rendering them less effective under natural conditions compared to controlled environments like greenhouse experiments or laboratory settings [255]. This is why advanced associations of microbial agents have been developed to enhance the efficacy of microorganisms in improving soil health. Interestingly, recent studies have shown that physical and metabolic interactions within microbial associations help preserve beneficial properties that support soil health, in contrast to their individual components [256,257]. By adopting this type of research, we can explore the eventuality of using known industrial microorganisms together in a solid community to strengthened their desired functions in a numerous domains like biotechnology, dentistry, medicine and also food processing [258–260]. Likewise, for environmental protection, especially in the case of soil, this sort of association can become handy to alleviate contamination and control soil-borne pathogens [261,262].

6.1 Nutrient Cycling and Organic Matter Decomposition

The rhizosphere in complex regions helps in the control of physicochemical interactions of the soil, such as chemical signals that are exchanged between microbial communities and inhabiting plants, and also plant growth [263,264]. Nutrients consumed by microbial biomass are incorporated into soils in the form of useful organic matter linked with minerals, which are progressively released to improve soil quality [265,266]. There are microbial communities behind these processes that are crucial for the functioning of fertile soils. These processes are the basis for cycling minerals such as K, Fe, B, C, N, P, and S. Such microorganisms are often perceived as positive indicators of key soil functions in nutrient cycling because they can directly absorb minerals for slow and continuous release [267]. Vital soil enzymes that are produced by microbes are also employed as indications in various biogeochemical cycles for sufficient nutrient recycling [268]. Also, in soils that are naturally rich in nitrogen, microorganisms that are known for nitrogen cycling can be considered as an indicator for improving soil nitrogen and maintaining it. Additionally, in this regard, an association between fauna, flora, and microbial communities are important actors in biological nitrogen that makes it more available for plant roots by decomposing N-rich plant residues and releasing organic nitrogen [268]. These elements, together with soil fertility, are required for plant growth and development. Likewise, the chemical and physical functions of soils rely heavily on biological features, which are often covered by various microbial populations [269].

The study by Hassan et al. (2023) demonstrated that bacterial consortia containing *Lysinibacillus* sp. and *Acinetobacter* sp. significantly enhance nutrient uptake and biofortification in tomato fruits. These consortia alter the soil microbiome by increasing the abundance of beneficial bacteria such as Proteobacteria, which play a crucial role in nutrient cycling and plant growth promotion. The mechanisms of action involve enhancing nutrient availability through processes like nitrogen fixation, phosphorus solubilization,

and the production of growth-promoting substances. Overall, this approach offers a sustainable method for improving crop nutrition, reducing reliance on synthetic fertilizers, and promoting environmental sustainability, thereby contributing to more sustainable agricultural practices [251]. The use of a microbial consortium comprising *Azotobacter chroococcum* 76A and *Trichoderma afroharzianum* T22 has been demonstrated to significantly enhance tomato yield, with increases of up to 48.5% under optimal water and nutrient conditions. This consortium not only boosts yield but also improves plant tolerance to water and nitrogen deficiencies by modulating the soil microbial community. The application of these microorganisms enhances nutrient availability and improves plant water relations, allowing tomatoes to adapt better to stress conditions. This approach offers a promising strategy for sustainable agriculture by improving crop resilience and productivity while reducing the need for chemical inputs [250]. Salinity significantly impacts crop growth, development, and reproductive biology. The accumulation of salts and chemicals reduces cultivable area, making it difficult to avoid abiotic stress factors. The addition of microbes, such as *Bacillus* sp., *Delftia* sp., *Enterobacter* sp., and *Achromobacter* sp., enriches soil without adverse effects. A study evaluated the effects of microbial consortia on tomato growth and mineral uptake under salt stress and normal soil conditions. Salinity treatments were established by mixing soil with seawater, and seedlings were inoculated with microbial consortia. The results showed that salt treatment significantly affected leaf, shoot, and root dry weight; shoot height; number of secondary roots; chlorophyll; and mineral contents in uninoculated seedlings. However, bacterized seedlings sown under saline soil increased leaf, shoot, and root dry weight; leaf number; shoot length; root length; secondary roots; and chlorophyll content. The inoculation of microbial consortia produced more secondary roots, accumulating more minerals and transporting substances to the plant, resulting in higher biomass and growth [270]. Microbial consortia appear to be the best alternative and cost-effective approach for managing soil salinity and improving plant growth under salt stress conditions [227]. This is a clear example demonstrating that the microbial population can directly contribute to soil fertility and crop yield. Hence, they serve as strong indicators of improved soil health, as they collectively drive decomposition processes [271].

6.2 Production of Phytohormones and Plant Growth Promotion

Microorganisms naturally create phytohormones such as gibberellins, indole acetic acid (IAA), cytokinins, and ethylene, which regulate plant growth and development [272]. Rhizobacteria and cyanobacteria are essential for plant growth, providing nitrogen, suppressing diseases, and producing vitamins and phytohormones. Cyanobacteria can photosynthesize, fix nitrogen, and stimulate rhizogenesis, aerial growth, and carbon supply. This study investigated the effectiveness of consortia using heterotrophic bacteria and cyanobacteria in developing tomato seedlings. The microbial collection consisted of three cyanobacteria (SAB-M612 and SAB-B866) and GS (unidentified cyanobacterium) and two phosphate and potassium solubilizing heterotrophic bacteria. The study found that the most compatible consortia were obtained by combining SAB-B866 and GS cyanobacteria with either of the two heterotrophic bacteria. Cyanobacteria GS promoted the growth of both rhizobacteria *in vitro*, while Cyanobacteria SAB-B866 stimulated tomato seedling growth in planta, leading to greater aerial development. The artificial formulation of microbial consortia can have positive synergistic effects on plant growth, making them of great agrobiotechnological interest [273].

GAs are also reported as regulators of plant growth by degrading DELLA proteins [178] and also as stimulators of elongation in plants and germination [274]. Adding to plant growth promotion properties. Plants treated with IAA-producing *Azospirillum* sp. showed improved host immunity against diseases [275]. As cytokinins are vital for cell division and defense responses against biotrophic plant diseases [178], it is widely reported that the increase in the level of cytokinins in plants can be microbe-mediated [276,277],

thus, phytohormone-producing microbial communities are linked to plant growth promotion and can serve as indicators in plant health management. All this data about bacterial and fungal strain secretions has led the road to producing microbial inoculants for plant growth promotion, biological control of pests and pathogens, bioremediation of polluted soil locations, and the breakdown and degradation of agricultural wastes [268,272,278]. That is why eco-friendly agriculture promotes microbial biofertilizers, which perform specialized activities for fertile, productive, and sustainable soils, improving plant stress tolerance and agricultural yield [279–281].

As an example of studies utilizing microbial consortia for plant growth promotion. Additionally, plants inoculated with the bacterial consortium exhibited improved growth rates, increased flowering, and enhanced fruit. Another study by Cirillo et al. 2023, explored the combined inoculation of *Azotobacter* (a nitrogen-fixing bacterium) and *Trichoderma* on various crops and showed that this microbial consortium significantly enhanced the production of phytohormones such as IAA and gibberellins [250]. Additionally, crops treated with this combination demonstrated improved growth metrics, including root length, shoot height, and overall biomass compared to untreated controls [250].

7 Conclusion

In contemporary agriculture, microbial consortia provide a novel and sustainable strategy for enhancing plant resilience, production, and health. These consortia provide a potent substitute for chemical fertilizers and pesticides by utilizing the advantageous interactions between various microorganisms. These consortia offer several benefits, including improved soil structure, increased tolerance to abiotic stressors, enhanced nutrient availability, and pathogen suppression. Microbial consortia's potential for sustainable crop management is highlighted by their capacity to stimulate plant defense mechanisms through ISR and SAR, as well as their capacity to enhance plant growth through nitrogen fixation, phosphorus solubilization, and phytohormone production.

The ability of microbial consortia to inhibit illness is among their most important contributions. Consortia like *B. subtilis* and *T. harzianum* or *P. fluorescens* and *B. amyloliquefaciens* have shown high efficiency against soil-borne diseases like *F. oxysporum*, *R. solani*, and *P. infestans* by competing with pathogens for nutrients and space, generating antimicrobial compounds, and triggering plant immune responses. Furthermore, microbial consortia contribute to improved soil health by fostering microbial biodiversity, enhancing soil aggregation, and increasing water retention capacity all of which are critical for maintaining soil fertility and structure over time. Additionally, microbial consortia are essential for reducing the effects of abiotic stressors such as salt, drought, and heavy metal toxicity. Beneficial bacteria help plants resist adverse climatic circumstances by generating antioxidant enzymes like catalase and superoxide dismutase, as well as osmoprotectants like proline and trehalose. In areas with harsh weather, this capacity to reduce stress is essential for stabilizing crop production and adjusting agricultural systems to climate change.

The agricultural industry may shift to more environmentally friendly and sustainable farming methods by incorporating microbial consortia into ICM systems. By lowering production costs and minimizing chemical pollution and soil degradation, the use of microbial-based treatments will lessen dependency on synthetic agrochemicals and promote environmental preservation. Microbial consortia will become more and more important in sustaining ecological balance while guaranteeing long-term agricultural production and food security as the world's food demand rises. To sum up, microbial consortia provide a revolutionary approach to sustainable agriculture by striking a balance between environmental responsibility and production. Even if there are still obstacles to overcome, achieving their full potential in global farming systems will require more study, improved technology, and regulatory assistance.

Despite their advantages, there are several obstacles to overcome before microbial consortia may be successfully included into extensive agricultural systems. Their efficacy may be impacted by variations in soil composition, environmental factors, and native microbiota, necessitating the development of optimal formulations suited to particular crops and agroecosystems. To guarantee uniform outcomes, treatment techniques including foliar sprays, root inoculation, and seed coating must also be standardized. Adapting the application of microbial consortia to various agricultural contexts will need regular monitoring of microbial populations, soil health, and crop performance.

Improving the stability and effectiveness of microbial consortia in outdoor settings should be the main goal of future studies. Improvements in microbial formulations, their persistence in soil, and their capacity to respond to a variety of climatic settings can all be facilitated by developments in metagenomics, synthetic biology, and microbial engineering. Furthermore, to maximize their effectiveness and reduce any possible ecological disturbances, it will be essential to comprehend how microbial consortia interact with the natural soil microbiome.

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