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Review Article

Insights into the functional role of tea microbes on tea growth, quality and resistance against pests and diseases

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Abstract

Tea is an economical and most widely used beverage across the globe owing to its unique fragrance and flavor. Plant microbe interaction has emerged as an important topic which got the attention of scientists to improve plant performance. Tea microbes remained a prominent research topic for scientists over the years as tea microbes helps in nutrient cycling and stress management which in turn improve the tea growth, yield and quality. The roots of tea plants are colonized by various microbes including arbuscular mycorrhizal fungi (AMF), bacterial communities, and endophytes increase root growth, development and nutrient uptake which in turn improve tea growth, yield and quality. These microbes also increase the concentration of nutrients, amino acids, soluble proteins, flavonoids, catechuic acid, glucose, fructose, sucrose contents caffeine, and polyphenols concentration in tea plants. Besides this, these microbes also protect the tea plants from harmful pest and diseases which in turn leads to an appreciable improvement in plant growth and development. The most important goal of any farming system is to establish a system with production of maximum food while minimizing impacts on the environment. The present review article highlights the role of various microbes in improving the growth, yield and quality of tea plants. In addition, we also discussed the research gaps to improve our understanding about the role of tea microbes in improving tea growth, yield, pest and diseases resistance. We believe that this review will provide a better insight into the existing knowledge of tea microbes in improving tea growth and yield.

Keywords: AMF; disease; growth; microbes; quality; tea

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Introduction

Tea is an important and extensively cultivated beverage across the globe (Bora and Bora, 2021). It is an imperious economic crop widely grown in China and South Asia and it contains a significant amount of phenolic compounds and minerals (Wan, 2003; Chen and Lin, 2015). Tea is mainly produced in Asia, Africa, Caspian Seas and South American countries. China, India, Kenya and Sri Lank are the major tea producing countries and they have a share of 75% in global tea production. Globally, 6,497,443 tons of tea are produced every year which has a global market value of 207.1 billion USD (FAO, 2020). Tea is long duration crop and it is subjected to diverse pests and disease attach which cause a substantial reduction in crop growth and yield (Mareeswaran *et al*., 2015). Globally, inorganic chemicals have been used to remedy this problem (Adesmoye and Kloepper, 2009). However, the application of chemicals to tea is prohibited owing to various reasons including soil deterioration, ground water pollution, residual effects in tea plants followed by the development of resistance and outbreak of secondary pests (Gurusubramanian *et al*., 2005; Hazarika *et al*., 2009; Saha and Mukhopadhyay, 2013). Moreover, the inappropriate use of chemicals to control pests and diseases also poses a serious threat to soil health and the environment. Therefore, now focus has changed to improve crop performance and manage diseases by using economical and ecologically safe methods (Bag *et al*., 2022).

Considerable efforts are being made across the globe through the use of alternative biological approaches, agricultural practices and microbes to improve crop growth, maintain soil health and productivity and reduce the infestation of pests and diseases (Fernando *et al*., 2005). Soil is a dynamic natural environment having an intense plant-microbes interaction that significantly affects the crops by initiating the production of growth hormones and harnessing essential nutrients (Bhattacharyya and Jha, 2012). Different microbes including rhizobia, arbuscular mycorrhizal fungi (AMF), actinomycetes and diazotrophic bacteria play an imperative role in nutrient cycling and their availability to host which in turn improves plant growth (Saharan and Nehra, 2011). Besides this soil microbes also affect the soil physio-chemical and biological properties which positively affect the plant growth and development (Saharan and Nehra, 2011).

Tea rhizo-sphere has been investigated recently in terms of plant microbe interactions. The growth of tea is hampered by soil temperature, poor nutrient availability and pruning. It has been documented that AFM significantly improve plant growth by increasing the plant nutrient uptake capacity (Shao *et al*., 2021) and nutrient availability to plants (Bag *et al*., 2022). AMF association significantly improves the nutrient mobilization and ensures better nutrient availability thus resulting in a significant increase in plant growth and development (Abbasi *et al*., 2015). Recently, endophytes also emerged as important microbes and it has been noted that colonize plants and produce secondary metabolites microbiologists and also provide protection to plants against different pests and diseases (Yan *et al*., 2018). Endophytes also improve the plant growth by nitrogen fixation, phosphorus solubilization, and production of indole-3-acetic acid (IAA), and improving the activity of 1-aminocyclopropane-1-carboxylate (ACC) deaminase which in turn improve the plant growth and development (Yan *et al*., 2018).

The rhizosphere is considered to be the heart of soil and it has direct plant microbe interaction. The plant roots provide photosynthates for microbial growth which in return facilitate plants growth and subsequent development (Banik *et al*., 2014; Olanrewaju *et al*., 2019). Besides this, microbes also play an important role as biocontrol agents to control various pathogens and diseases (Rungsirivanich *et al*., 2020). The identification of variety as well structural make of microbes is critical for ensuring their long-term use in tea gardens. The present review highlights the importance of various known and putative microbes native to tea soils for improving the growth, yield and quality of tea and resistance to pests and diseases. Moreover, we also shed light on various research gaps that must be fulfilled in future research studies for improving tea growth, yield and quality.

The role of soil microbial inoculants as bio-fertilizers

Soil is a rich environment and its health is significantly affected by different parameters including microbial growth, root exudates and different abiotic and as well as biotic factors (Bhattacharyya and Jha, 2012). The diversity of microbes and microbial interactions in soil are very complex and they significantly affect crop growth and soil health (Bhattacharyya *et al*., 2014). The microbes are considered essential for any ecosystem owing to role in biogeochemical cycles, nutrient acquisition, decomposition of soil organic matter (SOM), water uptake, and pest and disease control. The microbial bio-pesticides and bio-fertilizers are considered as an effective tool for pest management (Bhardwaj *et al*., 2014). Microbial bio-fertilizers improve the N fixation, solubilization of phosphorus, production of growth promoting hormones, nutrients and water uptake which in turn improve plant growth and productivity (Miransari, 2011; Dodd and Ruiz-Lozano, 2012).

Microbial bio-fertilizers contain live micro-organisms and their field application improves the plant's growth, soil fertility and plant tolerance ability by increasing the supply of nutrients (Bhardwaj *et al*., 2014; Vessey, 2003). The microbial bio-fertilizers are considered to be safe because they help to reduce global warming and reduce use of chemicals and prevent the degradation of SOM (Mia *et al*., 2010). The microbial bio-fertilizers include PGPR (plant growth promoting rhizobacteria), AMF and actinomycetes which play a significant role in nutrient cycling and plant growth and development (Mishra *et al*., 2013). The application of PGPRs substantially improves the N and phosphorus (P) uptakes which indicate their beneficial impacts on soil nutrient cycling and their availability to plants (Rajendran and Devaraj, 2004). The tea industry has achieved a significant success in exploitation of bio-fertilizers and in recent years the use of bio-fertilizers has substantially increased the tea growth and productivity (Bhardwaj *et al*., 2014). Various strains of PGPR (Bacillus *pseudomycoides, Burkholderia, Enterobacter lignolyticus* and *Pseudomonas aeruginosa*) are being used as bio-fertilizers to improve the growth and productivity of tea (Chakraborty *et al*., 2013; Dutta *et al*., 2015). Likewise, the use of *Azotobacter chroococcum*, *Bacillus subtilis* and *Pseudomonas* has also increased the growth and production of tea (Nepolean *et al*., 2012; Pandey *et al*., 2013).

Tea plants treated with microbes showed a significant increase in plant girth, root length, productivity of young shoots (Pandey *et al*., 2013). The use of N-fixing bacteria (NFB), P-solubilizing microbes (PSMs), K-solubilizing microbes have a tremendous potential and their inoculation to tea plants significantly improve soil health, microbial growth, plant growth, yield and quality (Baby, 2002; Aggani, 2013). The various methods including seed treatments, soil and foliar sprays are used to apply microbial bio-fertilizers to tea plants. However, the application method depends on different cultural practices and type of plant materials (Mondal *et al*., 2015; Dutta *et al*., 2015). SOM plays a significant part in soil health and proliferation of microbes and soil rice in organic matter (OM) are considered to have luxuriant growth of beneficial microbes whereas soil with poor OM status has reduced and restricted growth of microbes (Dutta *et al*., 2015). In conclusion, soil microbes, improves nutrient availability and soil organic matter which in turn improve the growth and yield of tea.

Role of AMF in tea growth, and quality

It has been reported that 80% of plant species develop AMF association (Wang and Jiang, 2015). Tea plants colonized with AMF have better root growth, nutrient and water uptake resulting in a substantial increase in tea growth and development (Shao *et al*., 2019). AMF also increased the amino acid contents in tea plant leaves followed by an increase in genes expression involved in amino acid synthesis enzymes. Moreover, AMF also appreciably increases the concentration of total soluble proteins (TSP), glucose, phenolic and flavonoid in the leaves of tea plants (Shao *et al*., 2019). AMF generally considered as bio-fertilizers and AMF inoculation offers resistance to host plants against different biotic and abiotic stresses (Chandra and Banik, 2021). The significance of AMF in regulating the plant growth and development has gotten significant attention in recent times (Wu *et al*., 2019).

AMF colonization significantly improves root length, root dry weight and root volume which in turn improves the nutrient and water uptake and resulting in significant increase tea growth and development (Abbasi *et al*., 2015). AMF increases plant growth and development in normal and stressed conditions. AMF inoculation also reduce the use of chemical fertilizers and improve the soil health and therefore improve the tea growth, yield, leaf nutrient concentration and leaf quality (Bag *et al*., 2022). AMF colonization also increases the synthesis of flavonoid contents and it also increases the accumulation different secondary metabolites in tea plants (Zubek *et al*., 2015). The concentration of amino acids is also increased the tea plants inoculated with AMF (Baslam *et al*., 2013; Sanmartín *et al*., 2014).

Moreover, concentration of leaf nutrients (Shao *et al*., 2019) and whole polyphenol contents are also substantially increased in tea plants inoculated with *G. mosseae* (Zhao *et al*., 2014). Theanine is an imperative metabolite produced by tea plants (Sharma *et al*., 2018). Many AMF species including *Glomus intraradices, Glomus versiforme* and *Glomus etunicatum* substantially improved theanine, copper, iron and zinc contents in tea plant tissues (Dash *et al*., 2019). AMF positively affect nutrient acquisition and improves water uptake which leads to an appreciable increase in tea growth, yield and quality (Wu *et al*., 2019). Salt stress causes a substantial reduction growth of tea, nonetheless, AMF significantly improves osmolyte accumulation, and reduces the lipid per-oxidation and improves salinity tolerance (Liu *et al*., 2014).

AMF considerably increased the P concentration, encourage P absorption which reduce dependence on inorganic fertilizers and leading to significant improvement in soil health, nutrient availability and tea growth and yield (Mei *et al*., 2019). AMF also improves the tea quality and it also induced a significant impact on growth, yield and tea quality. Recently, it has been reported that AMF improves concentration of phytohormone, nutrient absorption, root growth, genes expression and tea biomass production (Shao *et al*., 2021). Moreover, AMF also increases concentration of polyphenol, amino acids, flavonoids, catechuic acid, TSP, glucose, fructose and sucrose contents (Abbasi *et al*., 2015; Wu *et al*., 2019; Begum *et al*., 2019; Phour *et al*., 2020). To summarize, microbes improve nutrient uptake, root growth and osmlytes accumulation thereby improve the tea growth and yield.

Role of bacterial communities in growth and quality of tea

Bacterial communities also play a crucial role in tea growth and yield. The bacterial families like *Pedosphaeraceae, Solibacteraceae*, and *Gemmataceae* play a significant role in tea growth and development (Bhattacharyya *et al*., 2020). Recently, it has been reported that bacterial strain (Serratia marcescens: ETR17 strain) significantly improved the tea growth and development and resistance against tea root and foliage pests (Dhar *et al*., 2018). In another study, *Burkholderia pyrrocinia* (P10 strain) obtained from the tea region showed an appreciable potential to be used as bio-fertilizer (Han *et al*., 2021). Tea rhizosphere has a wide range of bacteria including *Bacillus, Beijerinckia, Azospirillum, Comamonas acidovorans, Pseudomonas aeruginosa* and *Paenibacillus polymyxa* which improve the tea growth (Table 1) and development by increasing production of IAA, siderophorem, solubilization increasing resistance against pathogens (Chakraborty *et al*., 2012; Morang *et al*., 2015).

The bacteria colonizing the tea roots also produce growth promoting substances including terpenoids, steroids and diterpenes which substantially improved the tea growth and yield (Tshikhudo *et al*., 2019). In a recent study, *Pseudomonas and Bacillus* isolated from tea rhizosphere showed a significant potential to improve the plant growth and yield of tea plants (Vandana *et al*., 2018). The native strains of tea rhizosphere region improved the growth of tea plants. The Bacillus species is a viable option to improve tea growth owing to their appreciable ability to produce spores and sensitivity to different climate conditions whereas, *Pseudomonas* species are considered to be alternate option owing to their better colonization capacity and their ability to suppress the fungal diseases (Vandana *et al*., 2018; Arafat *et al*., 2020). In another study, it was noted *Enterobacter lignolyticus* strain collected from tea rhizosphere significantly increased the growth and development of tea clones (Dutta *et al*., 2015). Likewise, inoculation of tea plants with PGPR significantly improved the growth, yield and quality of tea plants (Chakraborty *et al*., 2006; Chakraborty *et al*., 2013). Bacterial strains like, *Brevibacterium* and *Lysinibacillus* have been found to possess important PGRP characteristics and they significantly improve the plant growth by production of IAA and solubilization of P (Borah *et al*., 2019).

Chopra *et al*. (2020) identified 23 isolates of bacteria from the Assam tea garden. The collected strains were tested for their potential to improve plant growth and their anti-fungal properties against fungal pathogens (*Fomeslamaensis, Corticium rolfsii*, and *Rhizoctonia solani*). They noted that *Brevibacterium sediminis* has excellent potential as PGPR and it also possesses excellent antifungal properties (Chopra *et al*., 2020). In another study, Shan *et al*. (2018) obtained a wide range of actinobacteria from tea plants. They identified 46 different actinomycetes and most common genus was Streptomyces. *Piscicoccus* and *Mobilicoccus*. These authors noted that this strain a have higher capacity to produce secondary metabolites and they also significantly increased the IAA production, and possess excellent anti-bacterial and anti-fungal activities (Shan *et al*., 2018).

Table 1. Effect AMF on growth, yield and quality of tea

AMF Species	Effects	Reference
Claroideoglomus etunicatum	AMF inoculation increased plant height, root and shoot biomass, total leaf area, root volume and leaf N, P, K, Ca, Mg, Mn and Zn contents of tea plants.	(Shao *et al.*, 2018)
Acaulospora scrobiculata (A.s.) *Glomus macrocarpum (G.m.),* *Rhizophagus intraradices* (R.i.)	AMF inoculation improved leaves per plant, leaf area, plant height, shoot and root length, and fresh and dry weight of roots and shoots.	(Sharma and Kayang, 2017)
Clariodeoglomus etunicatum	AMF inoculation in drought stress conditions in tea plant improved antioxidant enzyme (superoxide dismutase (SOD), catalase (CAT), guaiacol peroxidase, and ascorbate peroxidase) activities, AMF enhanced plant defense mechanism which ultimately and reduced the oxidative damage of drought stress	(Chun-Yan *et al*., 2020)
Glomus versiforme	AMF inoculation under salinity conditions improved growth, root and leaf N, P, Fe, Zn, and Mg. AMF also reduced water saturation deficit	(Liu *et al*., 2013)
Glomus etunicatum	AMF inoculation in tea plant under shading enhanced the plant height, root and shoots biomass, root length and volume, nutrients uptake except Fe, and stress resistance.	Sun *et al*., 2020)
Glomus mosseae	AMF inoculation alleviated the salinity stress in tea and improved the quality of tea leaves.	(Guo *et al*., 2021)
Glomus epigaeumg	AMF inoculation improved plant biomass, chlorophyll, leaf P, Fe, Zn, Mg and Cu. AMF also enhanced soil phosphatase activity	(He and Liu, 1994)
Glomus mosseae, *Glomus intraradices*	AMF inoculation increased the callusing rate, chlorophyll content, and root resistant against pathogens	(Chelangat *et al*., 2021)
Claroideoglomus etunicatum	AMF showed significant higher growth in root length, root and shoot biomass, plant height. AMF also increase phosphatase activity	(Shao *et al*., 2021)

Acaulospora spinosa, Glomus aggregatum, Glomus ambisporum, Glomus clavisporum, Glomus geosporum	AMF in acidic soils increased root/shoot length, dry weight; root /shoot ratio, caffeine contents, sugar contents polyphenols contents which improved the tea quality	(Singh *et al.*, 2010)

AMF: arbuscular mycorrhiza fungi, N: nitrogen, P: phosphorus, K: potassium, Ca: calcium, Mg: magnesium, Mn: manganese, Zn: zinc, Fe, iron, Mg: magnesium and Cupper.

Colletotrichum also colonize the tea plants and they significantly improved the tea growth, yield and quality (Liu *et al.*, 2015). Likewise, different N-fixing bacteria (*Azospirillum*) and P-solubilizing bacteria were identified from Indian tea soils and they significantly increase plant growth and resistance against pest and diseases (Cernava *et al.*, 2019). In conclusion, bacterial communities improve nutrient uptake, and synthesis of hormones, resulting in substantial improvement in yield and quality.

Role of endophytes in growth and development of tea

Tea plants also host different groups of endophytic microbes (bacteria & fungus) in their leaves, roots and stem. The diversity of endophytes colonizing the tea plants depends on tea genotypes, tissue specification and seasonal variations (Yan *et al.*, 2018). The endophytic bacteria colonizing tea plants can be categorized into seven classes, four phyla, thirteen orders, thirty-two genera and twenty-four families (Xie *et al.*, 2020). However, the most predominant members colonizing the tea are from four different orders including *Bacillales, Burkholderiales, Micrococcales*, and *Rhizobiales*. Moreover, members from orders of *Glomerellales, Xylariales, and Diaporthales* are major contributors in the various tissues of tea plants (Xie *et al.*, 2020).

Endophytic microbes provide secondary metabolite to plants and leading to a significant increase in tea growth (Rustamova *et al.*, 2020). Besides this, they also generate different growth regulators including siderophores, ammonia, ACC deaminase and phytohormones and improve the efficiency of macro and micro-nutrients which in turn improve the plant growth and development (Alurappa *et al.*, 2018; Banik *et al.*, 2019a). Endophytic fungus colonizing the tea plants also produces secondary metabolites which improve the plant growth and flavor of tea plants (Boruta, 2018; Xie *et al.*, 2020). The microbial mediated increase in phyto-hormones is a promising option to improve the improve the tea growth and yield (Figure 1) and tea endophytes is a viable option to induce the production of phyto-hormones which in turn improve tea growth and production (Mu *et al.*, 2021). Moreover, tea endophytes also produce volatile compounds with a biological activity which has tremendous potential to be used against different pathogenic agents including bacteria, fungus and pests (Mu *et al.*, 2021). The endophytic fungi colonizing the teat plants improve the tea growth and productivity and this endophytic fungus also potential to be used as bio-fertilizers for other crops (Nath *et al.*, 2015). In crux, endophytes improve the synthesis of siderophores, ammonia, ACC deaminase and phyto-hormones and the efficiency of macro and micro nutrients thus leading to a significant increase in growth and yield.

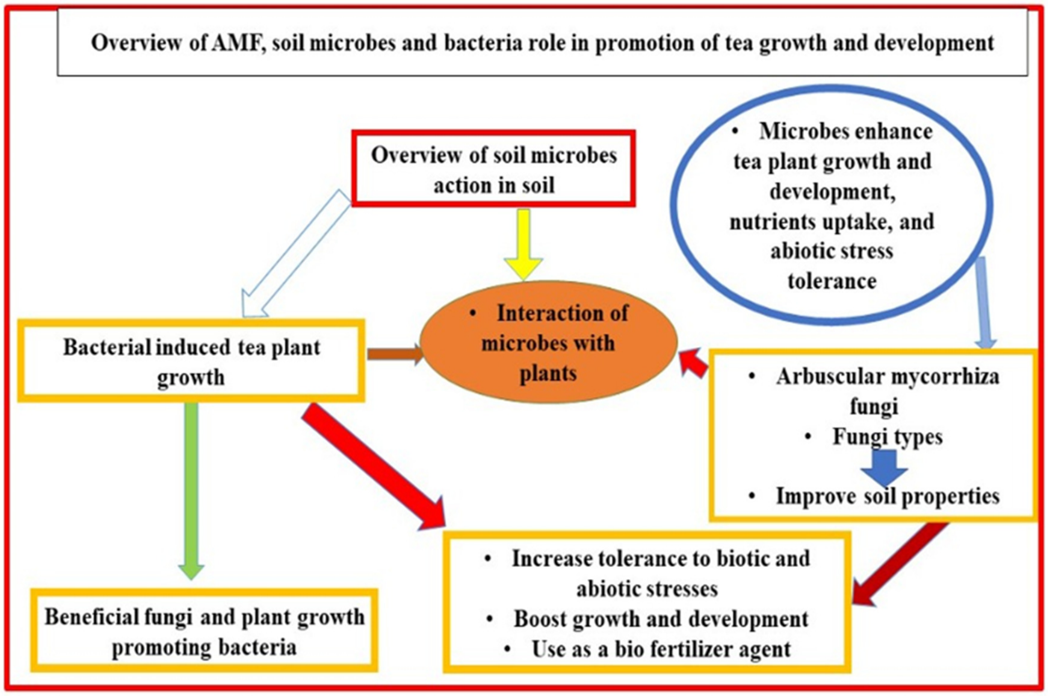

Figure 1. The soil microbes including AMF and bacteria improves, nutrient uptake, soil properties and water uptake which in turn improve the growth and stress tolerance in tea

Role of tea microbial pesticides to control tea-associated pests

Tea is long duration crop which is subjected to different pests that cause huge yield losses (Banik *et al.*, 2019b. The insects and pests pose a serious threat to tea cultivation that causes huge yield losses. Mites and insect pests affect tea cultivation and they can cause yield losses from 5-55% (Idris *et al.*, 2020). Microbial pesticides increase growth of plants by suppressing the activities of tea pests and pathogenic agents (Bhattacharyya and Sarmah, 2018). Mites and pests cause damaging effects to tea plants (Yu *et al.*, 2018) and *Ectropis obliqua* and *Gyropsylla spegazziniana* are prime mite and pests affecting the tea plants (Kakoki *et al.*, 2018). The microbes were discovered as an important biological weapon to control the pests of tea around 1970. The microbial pesticides are mostly produced by different entomopathogenic microbes (Idris *et al.*, 2020) and more than 40 bacterial and fungal taxa and 82 viral species efficient against tea pests have been identified (Idris *et al.*, 2020). The microbial agents including *Bacillus thuringiensis, Paecilomyces Beauveria, Euproctis* and *pseudoconspera* are important microbes to control the pests of tea plants (Banik *et al.*, 2014). The sustainable cultivation of tea focuses on the use of environment friendly approaches to control the pests of tea and reduce reliance on the use of synthetic pesticides.

Table 2. Effect of different microbes on growth, yield and quality of tea

Microbial species	Effects	Reference
Bacteria (BF9: *Bacillus megaterium* 47/9+ *Paenibacillus macquariensis* RC696)	Bacterial strains stimulated tea plant growth, leaf area, green leaf yield, chlorophyll contents and enzyme activities.	(Cakmakci *et al.*, 2021)
Basidiomycetes and actinomycetes	Interact with each other and improve the quality of tea	(Wang, 2019)
Bacteria (Azoto II-1, *Acinetobacter sp., bacteria* Endo-5, bacteria Endo-65 and Endo-76)	Bacteria improved the shoot growth of tea up to 17.26% higher than the control.	(Fauziah *et al.*, 2019)
Cyberlindnera, and *Aspergillus, Uwebraunia*	Increased activities of polyphenol oxidase, cellulase, and pectinase as promoted by bacteria genera	(Li *et al.*, 2018)
Pseudomonas fluorescens	Bacteria produce antibiotics, chelation of available iron, and synthesis of extracellular enzymes	(Bhattacharyya and Jha, 2012)
Okons (Azospirillum)	Enhance the nutrient level in tea seedlings or cuttings which resulted in higher yield and quality	(Phukan *et al.*, 2012)
Bacillus RC23 and *Paenibacillus polymyxa RC05*	Microbial inoculation improved the root length, number of roots, root quality, rooting percentage and root dry weight.	(Erturk *et al.*, 2008)
Paenibacillus, and *Arthrobacter*	These bacterial types showed high variability in utilizing various carbon sources in tea which increase yield.	(Çakmakçı *et al.*, 2010)

The use of microbes is a fascinating approach to control the pests of tea and in recent times it got attention around the globe (Bhattacharyya and Sarmah, 2018). Diverse microbial control methods have been acknowledged in various tea growing systems to produce pesticide free tea (Bhattacharyya and Sarmah, 2018). Moreover, to a great extent, production and utilization of microbial combinations is a beneficial option to improve tea growth and resistance against different pests (Bhattacharyya and Sarmah, 2018).

Role of tea microbial pesticides to control tea-associated diseases

Diseases are important biotic stresses that are causing huge growth and yield losses to tea crops across the globe. The intensity and incidence of diseases vary with climatic conditions, elevation and planting materials. Tea is susceptible to different tea pathogens and microbial tea rhizosphere also has many PGPR that improves the tea growth (Table 2) and resistance against different tea diseases (Phukan *et al.*, 2012). Various PGPR including *Aspergillus, Azotobacter, Azospirillum, Fusarium, Gliocladium Penicillium, Trichoderma* and *Pseudomonas* have appreciable potential to improve tea growth and resistance against tea pathogens (Mokhtar and El-Mougy, 2014). For instance, Bacillus subtilis significantly improves the resistance of tea against different diseases of tea including black rot, blister blight, branch canker, thorny stem blight and root diseases (Barthakur, 2011).

Sowndhararajan *et al.* (2013) studied the use of different biocontrol agents to control the diseases of tea. They used *Ochrobactrum anthropi* in combination with chemical fungicides to control the blister blight disease in tea. These authors noted that *Ochrobactrum anthropi* significantly managed the tea blister blight disease of tea. Likewise, Dutta *et al.* (2012) also found that the use of *Pseudomonas* aeruginosa managed brown rot disease of tea and improve resistance of tea plants against this disease (Dutta *et al.*, 2012). Anita *et al.* (2012) also documented that *T. atroviride* produce the secondary metabolites and enzymes that induce the resistance against the Phomopsis canker (Anita *et al.*, 2012). The synthesis of various enzymes including amylase, cellulase, chitinase, polygalacturonase and protease is linked with the antagonist activities of bio-control agents. For instance, *Bacillus* and *Pseudomonas* improved the resistance of tea plants against tea blight by increasing the synthesis of the aforementioned enzymes (Pallavi *et al.*, 2012).

Saravanakumar et al. (2007) tested the efficiency of *Pseudomonas* and *Bacillus* against blister blight disease of tea. They noted that these microbes significantly reduce the severity of blister blight which was linked with an increase in the synthesis of chitinase, glucanase, peroxidase (POD), phenolics and phenylalanine ammonia lyase (PAL). In another study, Premkumar *et al*. (2012) studied the efficacy of *Bacillus*, *Pseudomonas* and *Trichoderma* against the different fungal pathogens. The use of these microbes significantly increased the resistance and reduced the severity of eye spot disease of tea plants (Gnanamangai and Ponmurugan, 2012). Actinomycetes also have appreciable potential as bio-control agent and they can significantly manage the disease of tea (Bhattacharyya *et al.*, 2015). The *actinomycetes* including *Streptomyces nojiriensis, Streptomyces griseoluteus* and *Streptomyces somaliensis* are very effective (Figure 2) to control the different diseases of tea (Barthakur, 2011). The use of microbes to control diseases is an effective approach and it reduces dependence on chemical substances and it also improves the quality of soil and quality of tea production. The application of microbes is crucial to soil type and soil type significantly affects the efficiency of microbes to suppress diseases (Wardle *et al.*, 2004; Hazarika *et al.*, 2009). In the light of aforementioned findings increases the synthesis of different enzymes and nutrient availability and uptake which in turn improve tea growth and yield.

Interaction between tea rhizosphere microorganisms and environmental factors

Soil nutrients, pH, and water holding capacity are important components of soil that significant affect the abundance of soil microbes (Greenlon *et al.*, 2019). The microbe's diversity in soil rhizosphere has strong association with environmental factors (Figure 3). The soil properties are significantly changed owing to different rhizobacteria and the application of chemical fertilizers (Wang *et al.*, 2021). Soil microbes play an appreciable role in ecosystem stability, soil heath and soil functioning. The planting species, soil properties and farming practices significantly affect the microbial population in tea rhizosphere. Different authors noted a complex relationship between tea microbes in environmental factors in tea plantations (Li *et al.*, 2016). Recently, the rhizosphere of tea has been studied in detail and noticeably from the prospective of plant microbe interactions. These discoveries have opened a new window for future research in the domain of soil microbe interaction in tea plantations. The abundance and variety of microbes colonizing the tea plants is varied owing to geographical surroundings (Xie *et al.*, 2020).

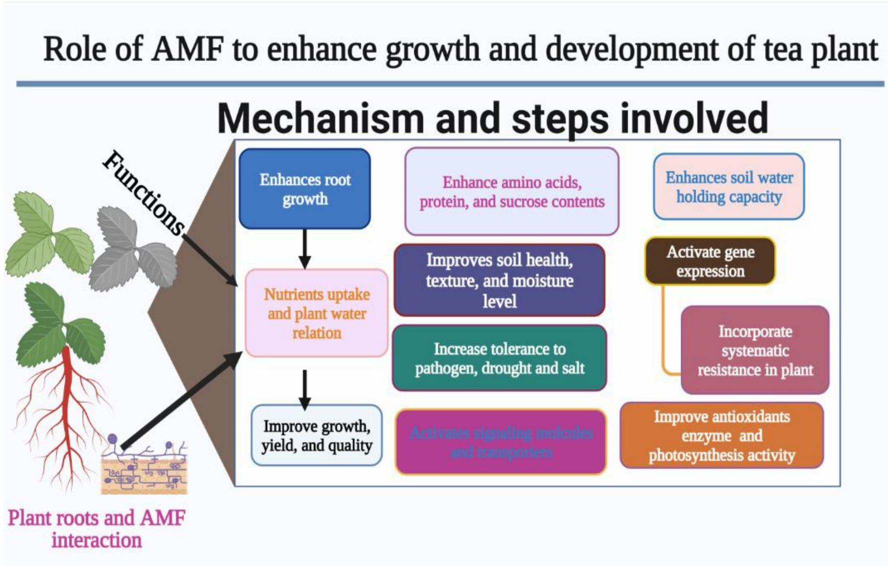

Figure 2. AMF enhances root growth, nutrient uptake, soil water holding capacity, genes expression, photosynthetic efficiency and antioxidant activity therefore improve the tea growth, yield, and quality and resistance against stresses

The long-term tea production boosted the abundance of microbial N and carbon while decreases the metabolic quotient (Li *et al*., 2017). The most abundant bacteria genera found in tea plantations are *Bacillus, Paenibacillus, Enterobacter, Pseudomonas* and *Acinetobacte* and they effectively improved the soil nutrient status, growth and yield of tea plants (Shang and Liu, 2021). PGPRs not only improve the soil nutritional status but they also restrict the growth of tea infections by producing various antibiotics, antifungal and insecticide compounds (Wang *et al*., 2021). Recently, it has been documented that degraded soil ecosystems can be remediated by using microbial abundance (Wang *et al*., 2019). Thus, the addition of organic matter, microbial fertilizers and the selection of suitable varieties can alleviate the issues of tea plantations (Bag *et al*., 2022).

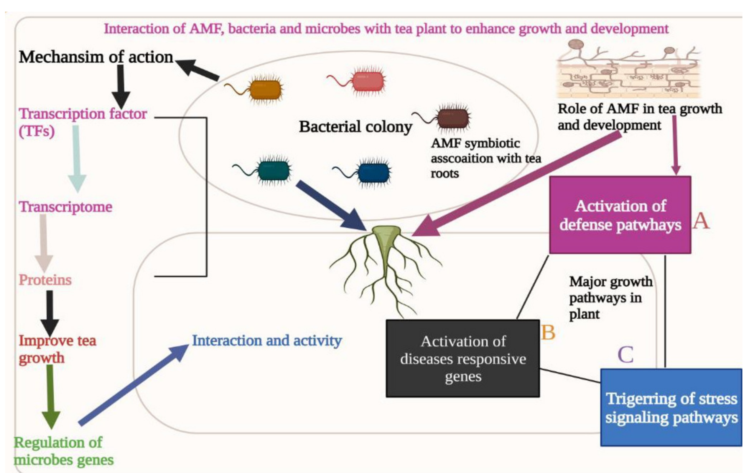

Figure 3. Interaction of AMF, bacteria and microbes in tea rhizosphere. Microbes enter into cell of tea plants by molecular receptors and they modulate genes expression pathways that are linked with defense responses, resistance against diseases and growth promotion of tea plants. The microbes also modulate the genes expression which influences the environment as well as growth of plants

Use of microbe's diversity sustainable production of tea

Microorganisms play a critical role in the agricultural production system. The development of a balanced and productive ecosystem is crucial for the survival of earth. The world is transferring to ecologically safe and economical production systems to increase the per unit production of tea (Gebrewold, 2018). The extensive use of chemicals induces negative impacts of soil health and their prolonged us also impose negative impacts on soil nutrient status and microbial diversity. Therefore, in this context use of modern production practices and biotechnological approaches are in high demand to improve soil health, growth and yield of crops. A huge quantity of synthetic fertilizers has been used over the years for the plantation of tea and long-term use of chemical substances has degraded the soil quality and tea yield (Chakraborty *et al*., 2013). Therefore, there is dire need to reduce the use of chemical substances in tea production and replace it biological agents to enhance soil fertility, tea quality and resistance against pests and diseases (Vandana *et al*., 2018).

AMF, microbes and PGPR showed beneficial impacts on tea growth, soil health and the environment. These aforementioned microbes also enhanced the immunity of plants by affecting the diverse cellular metabolisms and preventing the attack of pests and diseases. PGPR are most effective and promising microbes that improve the plant growth and soil without contaminating our environment region (Vandana *et al*., 2018). The increase in plant growth and resistance against pest and diseases following PGPR is linked with the production of siderophore, HCN (hydrogen cyanide), antibiotics and increase in soil nutrient status and improvement in soil health (Vandana *et al*., 2018). Nonetheless, a few concerns must be solved for these microbes for their long term uses. Moreover, AMF symbiosis also plays a significant role in plant performance; therefore, it should also keep in mind when using these microbes.

The screening and use of suitable pairing microbes in inadequate soils reduce the use of mineral fertilizers which improve the soil quality and production and quality of tea. Moreover, recognizing the AMF and other microbial induced stress tolerance and increase in crop production might help to further increase in crop production. Microbes and AMF must also be investigated at all levels to understand their functioning as bio-fertilizers and bio-control agents to improve agricultural productivity (Bag *et al*., 2022). The rhizospheric engineering to promote positive plant microbe's interactions would also be a major concern in the future. However, rhizosphere engineering can create new opportunities to reduce the use of pesticides for sustaining environmental health. The recent biotechnological approaches such as can used to alter the expression of different genes. This would be a blueprint for microbes, commencing with the organism, finding genes, and producing the modified microbes that can be transferred into tea plants. This will surely improve the tea growth, yield and quality while it will reduce the reliance on chemical fertilizers.

Conclusions

Plant microbes have a significant potential to improve crop production and plant resistance against different stresses. Here in this review, we have discussed the role of various microbes in improve the growth, yield and quality of tea and the resistance of tea plants against different pests and diseases. Tea microbes improve nutrient cycling, water and nutrient uptake which in turn improves the yield of tea plants. Moreover, these microbes also improve the accumulation of nutrients amino acids, soluble proteins, flavonoids, catechuic acid, glucose, fructose, sucrose contents caffeine, polyphenols, bio-active compound concentration in tea plants. Moreover, these microbes also work as biofertilizers and fulfill nutrient needs which are a major advantage of these microbes. The use of pesticides and fertilizers is a fatal option it causes environmental and health issues. Therefore, microbes also offer the bio-control of various pest and diseases associated with tea which in turn improves the growth and yield of the tea plants. However, there are still many unanswered questions that should be addressed in future studies. Extensive research is needed to explore the mechanism associated with different microbes to improve the yield and quality of tea. Only limited microbes have been investigated therefore it would be fascinating to conduct research on various microbes and their interaction with tea. The role of tea microbes must also explore in full detail against different pests and diseases attacking the tea plants. The genes governing microbial mediate growth and development in response to stress signaling must also be studied in future research. The recent improvement in sequencing and genome editing strategies identified the functions of various bacterial genes and these novel techniques can be used to alter the soil micro-biota which can enhance the tea growth, yield and resistance against pest and diseases. Besides this, the use of microbes can bring revolution in agriculture to fulfill the food needs of the raising population. Therefore, in the light of aforementioned facts research should be conducted to increase tea productivity while reducing the toxic effects of agro-chemicals for coming generations.

Authors' Contributions

Conceptualization; XZ; Writing - original draft: XZ; Writing - review and editing: HL, DH, MIA, JS, SL, AM, SL, JP, AP, MA and MUH.

All authors read and approved the final manuscript.

Ethical approval (for researches involving animals or humans)

Not applicable.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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