Open Access

Phytopathogenomics and Disease Control., ***2023, 2(2).87-94***
ISSN (Online):2957-5842; ISSN (Print):2957-5834
DOI: https://doi.org/10.22194/Pdc/2.1025
https://societyfia.org/journal/PDC

Microbial Marvels in Cotton Farming: Unveiling the Potential of Plant Beneficial Microbes for Enhanced Growth and Disease Resistance in Pakistan

Hafiz Tanvir Ahmad[1]*, Muhammad Iqbal[1], Ifrah Amjad*[2], Usama Kamal[2], Zeeshan Ali[3], Zain Ul Abdin[2], Hafeez Ullah Rafa[4], Mahmood Ul Hassan[5], Ghulam Mustfa Siddiqui[6], Rashad Ul Sher[7], Muhammad Ahsan Iqbal[2], Muhammad Nouman Khalid[2] and Tahir Majeed[8]

[1]National Cotton Breeding Institute, The Islamia University of Bahawalpur, Pakistan; [2]Department of Plant Breeding and Genetics, University of Agriculture Faisalabad, Pakistan;[3]Department of Agronomy, University of Agriculture Faisalabad, Pakistan;[4]Pesticide Quality Control Laboratory Kala Shah Kaku, Pakistan;[5]Sugarcane Research Institute, AARI, Faisalabad, Pakistan;[6]Vegetable Research Station Raiwind, Lahore, Pakistan;[7]Agronomic Research Station, Farooqabad, Pakistan; [8]Soil and Water Testing Laboratory for Research Thokar Niaz Baig Lahore, Pakistan
*Corresponding author's e-mail: hafiz.tanvir@yahoo.com; ifrahnoumanpbg@gmail.com

Cotton is a crucial cash crop in Pakistan, playing a pivotal role in the country's economy, agricultural sector, and employment opportunities. Its cultivation spans over 3 million hectares, primarily concentrated in the Punjab and Sindh provinces. Cotton production in Pakistan contributes significantly to the country's foreign exchange earnings, accounting for a substantial portion of its exports However, cotton pest and disease management is always a challenge as their impact change over time. The widespread use of agrochemicals and synthetic pesticides in major field crops poses significant threats to human and animal health, as well as environmental degradation. Use of beneficial microbes for sustainable cotton production can be a natural ally in the field, as they promote the plant growth as well as protect them from disease, insects and pests. They act as a reservoir of beneficial metabolites, enzymes, and nutrients, and they play a crucial role in biological pest control and disease resistance induction. Additionally, PGP rhizobacteria possess bioremediation potential, enabling them to phytoextract and detoxify pollutants and pesticides. Beneficial microorganisms like PGPR hold immense potential to replace and supplement these toxic chemicals, offering promising applications in organic farming and contributing to sustainable agricultural practices. Despite their potential, only a limited number of bio-formulations have been developed using PGPR strains with plant growth promotion, metabolite production, enzyme synthesis, nutrient mobilization, and biocontrol activities. An increasing body of evidence underscores the potential of diverse microorganisms to enhance plant productivity and yield within cropping systems. Unlocking the full benefits of these advantageous microbes requires a profound understanding of their role in promoting growth, specifically in the realms of fertilization and disease control, along with the elucidation of underlying mechanisms. It is imperative to confront challenges associated with the application of plant growth-promoting (PGP) microbes. This review focuses on the application of PGP microbes in the context of cotton production. Given the scarcity of information on beneficial microbes for cotton production, a comprehensive examination of current research becomes crucial, especially given the increasing interest in cotton inoculants, particularly in developing nations. The heightened attention towards PGP applications underscores the importance of advancing sustainable agricultural practices.
Keywords: Cotton production, Biocontrol, PGP applications, Beneficial microbes, pest control, disease resistance.

INTRODUCTION

Cotton is a crucial cash crop in Pakistan, playing a pivotal role in the country's economy, agricultural sector, and employment opportunities. Its cultivation spans over 3 million hectares, primarily concentrated in the Punjab and Sindh province (Muhammad *et al.*, 2022) Over the past years, the cultivation of cotton and its acreage in Pakistan has been consistently diminishing, attributed to the swift spread of pests.

Ahmad, H.T., M. Iqbal, I. Amjad, U. Kamal, Z. Ali, Z.U. Abdin, H.U. Rafa, M.U. Hassan, G.M. Siddiqui, R.U. Sher, M.A. Iqbal, M.N. Khalid and T. Majeed. 2023. Microbial Marvels in Cotton Farming: Unveiling the Potential of Plant Beneficial Microbes for Enhanced Growth and Disease Resistance in Pakistan. Phytopathogenomics and Disease Control 2:87-94.
[Received 23 Aug 2023; Accepted 21 Oct 2023; Published 15 Dec 2023]

Plant beneficial microbes offer a multitude of benefits for augmenting plant growth. A promising way to manage soil-borne diseases like *Verticillium dahliae* is a use of PGR rhizobacteria which also have the potential to deal with notorious pathogens in organic farming. Researchers have found many entophytic bacteria that can fight against Verticillium dahliae (Khursheed *et al.,* 2022). Indole acetic acid (IAA), a phytohormone produced by some of these bacteria also help plants grow better and stronger. IAA helps plants grow more roots, which means they can get more water and nutrients (Lopes *et al.,* 2023)

Studied have revealed that entophytic bacteria, which can live inside plants, make plants stronger, and produce such chemicals that have the potential to kill fungi. These chemicals, like cellulase and chitinase, break down the walls of fungi, making it harder for them to infect plants (Muthu Narayanan *et al.,* 2022). Scientists measure the amount of these chemicals in bacteria by using a special test called the DNS method (Lu *et al.,* 2023). PGP rhizobacteria also induce systemetic resistance in plants. Induced systemic resistance (ISR) is when plants make changes induced by the bacteria to protect themselves from diseases (Yu *et al.,* 2022). Some of these changes include making special chemicals called enzymes, like polyphenol oxidase (PPO), peroxidase (POD), and phenyl ammonia-lyase (PAL), and producing more phenols. POD and PPO help make plant cell walls stronger, which makes it harder for fungi to get inside and damage the plant (Jha & Mohamed, 2022). Bacillus subtilis strain having the ability to produce (APX) ascorbate peroxidase and (PAL) phenylalanine ammonia-lyase reduced the bacterial blight about 30% (Le Thanh *et al.,* 2023). In the last decade, plant growth promoting (PGP) activities of effective microbes have been reviewed and their role in cotton production have been discussed (Pereg *et al.,* 2015) We shall discuss the mechanisms of effective microbes for plant growth promotion as well as their role as a biocontrol agent in recent years.

Bacterial Strategies for Augmenting Plant Growth: PGP rhizobacteria and rhizobia employ diverse mechanisms to enhance plant growth, productivity, and survival in varying conditions (Bhat *et al.,* 2023). Positive impacts include the production of plant growth regulators, osmolytes, and enzymes, along with increased nutrient availability, biofilm formation, and systemic tolerance induction (Bouremani *et al.,* 2023). PGPR inoculation under abiotic stress induces responses such as augmented K+/Na+ ratio, expanded root surface area, swift osmotic adjustment, and reduced ethylene levels. These mechanisms highlight the potential of PGPR as sustainable solutions for plant health and resilience in agriculture.

Phytohormone Production by Plant Beneficial Microbes: The synthesis of phytohormones, including ethylene, auxins, gibberellins, cytokinins, and abscisic acid by PGPR and rhizobia stimulates plant growth across diverse conditions (Fahad *et al.,* 2015). Indole acetic acid (IAA) biosynthesis influences root architecture, enhancing nutrient uptake. Cytokinins play a role in mitigating water stress effects, while gibberellic acid contributes to improved productivity. Dual roles of phytohormones and their modulation under environmental conditions showcase the adaptability of PGPRs and rhizobia in promoting plant growth (Qasim & Sciences, 2023) figure 1.

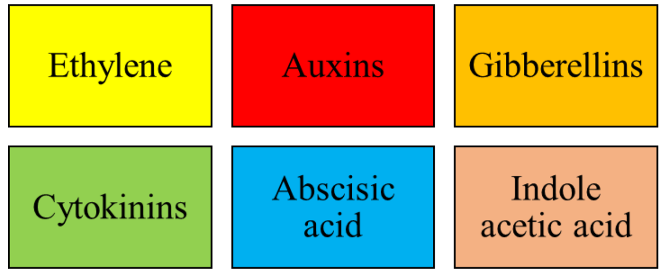

Figure 1. The Production of Phytohormones by Microbes That Are Beneficial to Plants

Osmolyte Production by Beneficial Microbes: Rhizobacteria exhibit resilience in the rhizosphere by producing osmolytes like sugars, amino acids, and quaternary amines, acting as osmoprotectants. These osmolytes reduce cytoplasmic osmotic potential, maintaining cell turgidity and preventing degenerative processes (Camaille *et al.,* 2021). They also function as molecular chaperones and free-radical scavengers, detoxifying reactive oxygen species. Enhanced proline and trehalose contents in plants demonstrate the role of osmolytes in maintaining growth under water deficit stress (Kosar *et al.,* 2019).

Enzyme and Antioxidant Production for Stress Mitigation: Rhizobacteria produce enzymes and antioxidants crucial for scavenging reactive oxygen species (ROS) and mitigating stress-induced ethylene. Rhizobacteria produced enzymatic scavengers and non-enzymatic compounds counteract ROS, ensuring cell viability (Das & Mukherjee, 2021). Studies on Mesorhizobium ciceri and Mesorhizobium mediterraneum link enzyme production with enhanced drought tolerance. ACC-deaminase activity in rhizobia contributes to stress-induced ethylene reduction. The multifaceted enzymatic and antioxidant arsenal of rhizobia showcases their role in promoting plant health (Stringlis *et al.,* 2019).

Nutrient Solubilization and Availability: Bio-fertilizers, including PGPR, play a crucial role in increasing both macro and micronutrient availability in crops (Kumar *et al.,* 2017). PGPR enhance N, P, and K uptake, reducing reliance on chemical fertilizers. Rhizobia solubilize phosphorus and produce siderophores, influencing iron availability. The ability to optimize fertilizer doses with PGPR supplementation underscores their potential in sustainable agriculture (Miteu *et al.,* 2023).

Biofilm Formation and Exopolysaccharides Production: Plant beneficial microbes capability to produce exopolysaccharides (EPS) contributes to drought stress alleviation and soil structure enhancement. EPS-producing rhizobia enhance crop tolerance and yield (Latif *et al.*, 2022). Biofilm formation on roots facilitates rhizobia colonization, stimulating root exudation and promoting biological activity. Bacterial adaptation to environmental stresses involves changes in LPS structure and osmotic stress-induced alterations (Rowlett *et al.*, 2017).

Induced Tolerance to Abiotic Stress and Biocontrol: Rhizobacteria induce systemic tolerance in plants through the production of osmoprotectants, phytohormones, and EPS, enhancing survival under drought. Volatile Organic compound producing bacteria induce drought tolerance, while ACC-deaminase-producing bacteria regulate stress ethylene, contributing to resilience. Rhizobia serve as biocontrol agents by producing antibiotics, siderophores, and chitinase, inhibiting pathogenic bacteria, fungi, and nematodes. The multifaceted activities of rhizobia make them valuable contributors to plant health and stress resilience (Abdelaziz *et al.*, 2023).

Growth Promotion Activities of Beneficial Microbes in Cotton: Bacteria are essential for promoting cotton growth, enhancing nutrient solubilization, and acting as chemical fertilizers (Ahmad *et al.*, 2023). Bacillus subtilis and Bacillus aryabhattai increase boll numbers, seed cotton yield, lint yield, and antioxidant activities. They also improve water retention and nitrate nitrogen retention in saline-alkali soil. Bacte-solubilizing bacteria like Bacillus sp. increase seed cotton yield and soil available phosphorus. Rhizobium sp. B02, a phosphate-solubilizing bacteria, enhances the efficient use of low-solubility fertilizers like rock phosphate (Sharath *et al.*, 2021). This suggests the potential application of Rhizobium genus as phosphate-solubilizing bacteria in improving cotton cultivation and optimizing phosphorus use (Zhou *et al.*, 2023).

In a single experiment, Rhizoctonia solani-caused wilting of cotton seedlings was treated using Pseudomonas aureofaciens as a biocontrol agent. Sahu *et al.* (2018) looked at the efficacy of cyanobacteria-based compost formulations as PGP and biocontrol agents in cotton. Furthermore, the mechanisms by which PGPR promotes plant development, produces systemic resistance, and controls infections biologically were investigated. According to Prasanna *et al.* (2016), Anabaena sp. and Calothrix sp. have shown promise as PGP and biocontrol agents in cotton. Bacillus subtilis Bbv57 has antagonistic properties against plant diseases, according to Thiruvengadam *et al.* (2022), suggesting that it could be useful as a biocontrol agent in the context of sustainable agriculture. Zebelo *et al.* (2016) evaluated the effects of PGPR (plant growth-promoting rhizobacteria) treatment on cotton plants in their investigation. Plant resistance to the beet armyworm was found to be enhanced by PGPR treatment, which also boosted gossypol levels and encouraged the expression of genes required for its manufacture (Table 1).

Scientists are very interested in plant growth-promoting rhizobacteria (PGPR) because of its ability to improve plant development and productivity in nutrient-deficient environments and to potentially reduce the use of dangerous agricultural pesticides. PGPR employed a wide range of tactics, including substrate competition, antibiotic production, lytic enzymes, and induction of systemic resistance, to prevent infections and promote plant growth. Understanding

Table 1. The activities of beneficial microbes in cotton that promote growth and development.

Microbial inoculant	Experimental system	Effects	References
Paenibacillus polymyxa IA7 + *Bacillus aryabhattai* IA20	Pot experiment	Improved the number of bolls, lint yield and seed cotton yield	(Ahmad *et al.*, 2023)
Bacillus velezensis	Greenhouse	Increased biomass; IAA, Sidrphore production	(Su *et al.*, 2023)
Bacillus subtilis	Pot planting	Improved cotton yield and growth under salt stress conditions.	(Zhou *et al.*, 2023)
Bacillus subtilis IA6 + *Paenibacillus polymyxa* IA7	Jar experiment	Enhanced the growth of cotton seedlings	(Ahmad *et al.*, 2021)
Acinetobacter sp.	Pot experiment	Number of bolls were increase	(Sharath *et al.*, 2021)
Rhizobium sp.	Glasshouse study	Significantly promoted growth, photosynthetic rate, stomatal conductance	(Zhou *et al.*, 2023)
Rhizobacteria	A field experiment	Improved the of the Leaf area index, photosynthetic rate, total number of bolls per plant, and seed cotton yield	(Majid *et al.*, 2020)
Bacillus subtilis strain Q3 and *Paenibacillus sp.* strain	Jar Experiment	Root and shoot fresh & dry weight	(Ahmad *et al.*, 2018)
Azotobacter chroococcum	Glasshouse study	To improve cotton growth by decreasing the N fertilizer dose	(Romero-Perdomo *et al.*, 2017)
Cyanobacteria	Glasshouse study	Enhanced germination, fresh weight, and microbiological activity in cotton plants.	(Prasanna *et al.*, 2015)
Bacillus fusiformis S10 *Pseudomonas aeruginosa* Z5 þ	Field trials	Enhanced growth and yield with abridged application of chemical fertilizer	(Yasmin *et al.*, 2013)
Raoultella planticola	Pot trials	Improved seed germination, plant height and weight	(Wu *et al.*, 2012)

how they function, how they can colonize new areas, and how they are formulated can help them advance as dependable parts of sustainable agricultural systems (Murthy *et al.*, 2021). In a separate study, Prasanna *et al.* (2016) investigated the effect of microbial inoculants on cotton seedling mortality in soil contaminated with Rhizoctonia solani. They found significant decreases in mortality and changes in bacterial populations in the rhizosphere. Numerous microbial inoculants have been shown to improve production, indicating that these compounds have the ability to both promote plant growth and prevent illness. The study's goal was to create biocomposts that would lessen cotton seedling damping-off by using talc and bentonite granules as carriers for Pseudomonas fluorescens strains. According to Ardakani *et al.* (2010), bioformulations were more effective than traditional fungicide therapy. This shows that both organic and inorganic carriers can improve the stability and efficacy of biocontrol-active bacteria, which are used to control plant diseases.

A family of soil bacteria known as PGP rhizobacteria (PGPR) improves the uptake of nutrients by plants, promotes seed germination, develops roots, and guards against many plant diseases. The potential of PGPR as effective biocontrol agents targeting plant diseases has been greatly enhanced by the recent advancements in their diversity, methods of action, and applications. According to Siddiqui (2006), biofertilization and disease prevention are two possible applications of this technology in agriculture. Of the eleven bacterial isolates linked to whiteflies that were examined in this study, *Erwinia persicinus*, *Bacillus pumilus*, and *Exiquobacterium acetylicum* were the most successful at reducing Bemisia tabaci, a variation of the fly. Given their proven effectiveness as biological control agents, these bacteria may be able to lessen the negative effects of whiteflies without the need for traditional pesticides. In light of the findings, more investigation into these bacterial isolates' potential as biopesticides to lower whitefly populations with a minimum of dependence on dangerous chemicals might be undertaken (Ateyyat *et al.*, 2009).

The effects of sooty fungus on cotton were studied using bacteria. According to reports, Bacillus cereus YUPP-10 significantly suppresses Fusarium wilt in cotton (Zhou *et al.*, 2023). Streptomyces rochei 42561, another biocontrol bacterium, has been shown by Huang *et al.* (2023) to have remarkable preventative properties against cotton blight and cotton greensickness. Furthermore, it was found that when exposed to sooty mold, Pseudomonas chlororaphis MT5 and Bacillus velezensis MT9 performed effectively as biocontrol agents. These bacteria also produced water-soluble antifungal and antibacterial chemicals, as well as volatile organic compounds (VOCs) having antifungal characteristics. The promise of endophytic bacteria for the biological treatment of cotton diseases is further supported by their identification, antibiosis ability against Fusarium oxysporium f.sp. and Rhizoconia solani kuhn, and their isolation from cotton cultivars (Ming *et al.*, 2004). Specifically, Bacillus sp. As such, the application of these bacteria as biocontrol agents presents promising opportunities for the prevention and management of cotton sooty mold.

Pseudomonas chlororaphis and protegen strains are able to manage plant diseases and eradicate insects through the production of virulence factors. Although these bacteria are commonly found in soil and roots, it is still unclear where they live and how they interact with arthropods (Hofte, 2021). Scientists have isolated P. chlororaphis strains and P. protegens from a variety of sources, including earth, myriapods, grassland soil, agricultural field soil, and healthy insect roots. Next, a thorough assessment of the isolates' capacity to eradicate insects, avert illnesses, and settle on hosts was conducted. Remarkably, the findings showed that the degree of insecticidal action was not significantly influenced by the isolation's origin or phylogenetic location. While P. chlororaphis strains showed significant diversity, P. protegens strains showed consistent phylogenetic, biocontrol, and insecticidal features. A thorough behavioral and genomic investigation revealed that the genes encoding different insecticidal components differed amongst closely related P. chlororaphis isolates with differing levels of insecticidal activity. These genetic alterations may be the cause of the decreased insecticidal efficiency seen in some isolates. Bacillus subtillis strain HMB28948 is useful in avoiding cotton damping-off. The strain demonstrated inhibitory effects against various diseases, including verticillium wilt and botrytis cinerea, Guo *et al.* (2021) (Table 2)

***Considerations for PGP Microbes in Cotton Production*:** Translating microbial benefits from controlled environments to field trials presents challenges, necessitating a comprehensive understanding of influencing factors (Highmore *et al.*, 2022) Factors like plant species, soil type, local microbial communities, and environmental variables impact microbial efficacy, emphasizing the need for careful selection and dual-action capabilities (Mitra *et al.*, 2022) Challenges in arid soils and economic considerations, including mass production and shelf life, require attention for successful microbial commercialization (Naorem *et al.*, 2023). The potential of co-inoculation strategies in mitigating field trial variability further supports the adoption of PGP microbes in cotton production (Ahmad *et al.*, 2023). The advantages of reduced environmental impact and compatibility with pest management position microbial inoculants favorably in comparison to chemical inputs (Elnahal *et al.*, 2022). The microbial inoculants should be tested in field condition extensively for evaluation their potential and improvement as well.

***Conclusion and Future Directions*:** Despite facing challenges, there is a growing exploration of diverse microorganisms with potent attributes for enhancing the growth of cotton plants. These microorganisms are

Table 2. Biocontrol agent for different pathogens.

Biocontrol agent	Pathogen/Pest/Insect	References
Bacillus sp. T6	*Verticillium dahliae*	(Zhang *et al.*, 2023)
Bacillus spp	*Xanthomonas citri pv. malvacearum*	(Sampathkumar *et al.*, 2023)
Bacillus velezensis	*R. solani*	(Su *et al.*, 2023)
Bacillus thuringiensis	*Spodoptera frugiperdaand Anticarsia gemmatalis*	(Gomis-Cebolla & Berry, 2023)
Beauveria bassiana	*Spodoptera litura (Fabricius)*	(Islam *et al.*, 2023)
Bacillus Rz141 and Streptomyces HC658	Fusarium oxysporum f.sp. vasinfectum race 4 (Fov4),	(Hofte, 2021)
Bacillus thuringiensis	*Spodoptera frugiperda*	(da Costa *et al.*, 2020)
Bacillus velezensis strain AL7	*Verticillium dahlia*	(Liu *et al.*, 2020)
Bacillus amyloliquefaciens, Bacillus velezensis, and Paenibacillus lentimorbus	*Ramulosis (Colletotrichum gossypii var. cephalosporioides)*	(Ferro *et al.*, 2020)
B. velezensis strains Bve2 and Bve12, B. mojavensis strain Bmo3, and Mixture 2	*M. incognita*	(Xiang *et al.*, 2017)
Pseudomonas spp., Bacillus spp., and Burkholderia sp.	Cotton leaf curl virus disease	(Ramzan *et al.*, 2016)

continuously being discovered and tested in real-world conditions, resulting in an increasing number of success stories. The positive outcomes of this research yield substantial financial benefits, manifested in reduced reliance on chemical fertilizers and pesticides, along with heightened productivity through increased crop yields. Additional advantages include the diminished presence of toxins in agricultural lands and a reduction in environmental pollution. Successful outcomes often depend on the synergistic application of inoculants endowed with complementary beneficial traits. For instance, the collaborative action of biofertilizers enhancing nutrient availability around the roots, combined with mycorrhizal fungi improving the root system, optimizes nutrient absorption by cotton plants. Indigenous microbes frequently prove most effective, seamlessly adapting to the specific environmental conditions of the targeted cropping system. However, in the case of biocontrol agents, these indigenous microbes must successfully compete with pathogens for resources efficiently to suppress pathogens.

Moreover, the identification and isolation of these advantageous microbial agents for augmentation highlight the importance of directing additional research efforts towards cultivating cropping practices that promote the safety of both indigenous and introduced beneficial microbes. This entails careful regulation of chemical inputs to prevent over application, which could hinder beneficial activity and inadvertently promote harmful microorganisms. Collaborative efforts are vital for developing technology aimed at screening and identifying microbes with advantageous traits, assessing their impact on cotton plants, testing strains for commercial viability, optimizing formulations for effective inoculant delivery, this includes the examination of soil microbial communities, the assessment of the impact of soil inoculation on soil health, and a comprehensive understanding of the wider repercussions of agricultural practices on particular microbial communities.

Pathogen-suppressive microbes can be isolated from pathogen buried in the soil propagules. Microbes that regulate pathogen populations through competitive colonization, particularly in sterilized soil, prove effective in excluding the growth of other harmful organisms. In conclusion, the ongoing pursuit of novel biocontrol microbes is of paramount importance in addressing issues of pathogenic resistance, especially considering the increasing global demand for cotton crops. Acknowledging the necessity for continuous innovation, interdisciplinary collaborations is the need of the hour and a more thorough understanding of plant microbe interaction in the soil.

***Authors' contributions*:** All authors contribute equally.
Funding: NA
***Ethical statement*:** This article does not contain any studies with human participants or animal performed by any of the authors.
***Availability of data and material*:** NA
Code Availability: NA
***Consent to participate*:** All authors are participating in this review study.
***Consent for publication*:** All authors have no objection in publication of this research paper.

REFERENCES

Abdelaziz, A.M., A.H. Hashem, G.S. El-Sayyad, D.A. El-Wakil, S. Selim, D.H. Alkhalifah and M.S. Attia. 2023. Biocontrol of soil borne diseases by plant growth promoting rhizobacteria 48:105-127.

Ahmad, I., M. Ahmad, Bushra, A. Hussain, M.Z. Mumtaz, G.H. Abbasi, F. Nazli, L. Pataczek and H.M.J.M. Ali. 2023. Mineral-Solubilizing Bacteria-Mediated Enzymatic Regulation and Nutrient Acquisition Benefit Cotton's (*Gossypium hirsutum* L.) Vegetative and Reproductive Growth 11:861.

Ahmad, I., M. Ahmad, A. Hussain and M.J.F.M. Jamil. 2021. Integrated use of phosphate-solubilizing Bacillus subtilis strain IA6 and zinc-solubilizing Bacillus sp. strain IA16: a promising approach for improving cotton growth 66:115-125.

Ahmad, M., I. Ahmad, T.H. Hilger, S.M. Nadeem, M.F. Akhtar, M. Jamil, A. Hussain and Z.A.J.P. Zahir. 2018. Preliminary study on phosphate solubilizing Bacillus subtilis strain Q3 and Paenibacillus sp. strain Q6 for improving cotton growth under alkaline conditions 6:e5122.

Ardakani, S.S., A. Heydari, N. Khorasani and R.P. Arjmandi. 2010. Development of new bioformulations of Pseudomonas fluorescens and evaluation of these products against damping-off of cotton seedlings. Pp.83-88.

Ateyyat, M.A., M. Shatnawi and M.S.J.J.J.B.S.Al-Mazra'awi. 2009. Culturable whitefly associated bacteria and their potential as biological control agents 2:139-144.

Bhat, M.A., A.K. Mishra, S. Jan, M.A. Bhat, M.A. Kamal, S. Rahman, A.A. Shah and A. P. Jan. 2023. Plant growth promoting rhizobacteria in plant health: A perspective study of the underground interaction 12:629.

Blagojev, N., M. Škrinjar, S. Vesković-Moračanin and V. L. Šošo. 2012. Control of mould growth and mycotoxin production by lactic acid bacteria metabolites 17:7219-7226.

Bouremani, N., H. Cherif-Silini, A. Silini, A.C. Bouket, L. Luptakova, F.N. Alenezi, O. Baranov and L.J.W. Belbahri. 2023. Plant growth-promoting rhizobacteria (PGPR): a rampart against the adverse effects of drought stress 15:418.

Calcagnile, M., M.S. Tredici, A. Pennetta, S.C. Resta, A. Talà, G.E. De Benedetto and P.J.B.C. Alifano. 2022. Bacillus velezensis MT9 and Pseudomonas chlororaphis MT5 as biocontrol agents against citrus sooty mold and associated insect pests 176:105091.

Camaille, M., N. Fabre, C. Clément and E. M. Ait Barka. 2021. Advances in wheat physiology in response to drought and the role of plant growth promoting rhizobacteria to trigger drought tolerance 9:687.

da Costa, F.S.S., L.B. Praça, A.C. Gomes, R.C. dos Santos, C.S. Soares and R. A. Monnerat. 2020. Bacillus thuringiensis Effect on the Vegetative Development of Cotton Plants and the Biocontrol of Spodoptera frugiperda 10:1889.

Das, S. and A.J.A.i.P.-M.I. Mukherjee. 2021. Impact of Plant Growth-Promoting Microbes (PGPM) in Plant Disease Management by Inducing Non-enzymatic Antioxidants pp.291-303.

Elnahal, A.S., M.T. El-Saadony, A.M. Saad, E.-S.M. Desoky, A.M. El-Tahan, M.M. Rady, S.F. AbuQamar and K.A.J.E.J.o.P.P. El-Tarabily. 2022. The use of microbial inoculants for biological control, plant growth promotion, and sustainable agriculture: A review 162:759-792.

Fahad, S., S. Hussain, A. Bano, S. Saud, S. Hassan, D. Shan, F.A. Khan, F. Khan, Y. Chen, C.S. Wu and P. Research. 2015. Potential role of phytohormones and plant growth-promoting rhizobacteria in abiotic stresses: consequences for changing environment 22:907-4921.

Ferro, H.M., R.M. de Souza, F.M.V. Lelis, J.P. da Silva and F.H. de Medeiros. 2020. Uso de bactérias para proteção do algodoeiro: controle de doenças, produtividade e qualidade de fibras 33:43-53.

Gomis-Cebolla, J. and C.S. Berry. 2023. Bacillus thuringiensis as a biofertilizer in crops and their implications in the control of phytopathogens and insect pests 79:2992-3001.

Highmore, C., G. Melaugh, R. Morris, J. Parker, S. Direito, M. Romero, F. Soukarieh, S. Robertson, N.J.n.B. Bamford and Microbiomes. 2022. Translational challenges and opportunities in biofilm science: a BRIEF for the future 8:68.

Höfte, M. 2021. The use of Pseudomonas spp. as bacterial biocontrol agents to control plant disease. p. *In* (ed^.) Microbial bioprotectants for plant disease management. Burleigh Dodds,

Huang, T., Y. Zhang, Z. Yu, W. Zhuang and Z.M. Zeng. 2023. Bacillus velezensis BV01 Has Broad-Spectrum Biocontrol Potential and the Ability to Promote Plant Growth 11:2627.

Islam, S.M.N., M.Z.H. Chowdhury, M.F. Mim, M.B. Momtaz and T.J.S.R. Islam. 2023. Biocontrol potential of native isolates of Beauveria bassiana against cotton leafworm Spodoptera litura (Fabricius) 13:8331.

Jha, Y. and H.I.J.G.P. Mohamed. 2022. Plant secondary metabolites as a tool to investigate biotic stress tolerance in plants: a review 74:771-790.

Khan, N. and A.O. Bano. 2019. Exopolysaccharide producing rhizobacteria and their impact on growth and drought tolerance of wheat grown under rainfed conditions 14:e0222302.

Khursheed, A., M.A. Rather, V. Jain, S. Rasool, R. Nazir, N.A. Malik and S. P. Majid. 2022. Plant based natural products as potential ecofriendly and safer biopesticides: A comprehensive overview of their advantages over conventional pesticides, limitations and regulatory aspects 105854.

Kosar, F., N.A. Akram, M. Sadiq, F. Al-Qurainy and M.J.J.o.P.G.R. Ashraf. 2019. Trehalose: a key organic osmolyte effectively involved in plant abiotic stress tolerance 38(606-618.

Kumar, R., N. Kumawat and Y.K. Sahu. 2017. Role of biofertilizers in agriculture 5:63-66.

Latif, M., S. H. Bukhari, A.A. Alrajhi, F.S. Alotaibi, M. Ahmad, A.N. Shahzad, A.Z. Dewidar and M. Mattar.

2022. Inducing drought tolerance in wheat through exopolysaccharide-producing rhizobacteria 12:1140.

Le Thanh, T., N.H. Hoang, K. Thumanu, C. Saengchan, J. Rayalu, R.S. Daddam, N.K. Papathoti, K.J. Buensanteai and Biol. 2023. AJAB.3):

Liu, H., Q. Zeng, W. Wang, R. Zhang and J. J. Yao. 2020. Complete genome sequence of Bacillus velezensis strain AL7, a biocontrol agent for suppression of cotton Verticillium wilt 9:10.1128/mra. 01595-01519.

Lopes, L.D., S.L. Futrell, E. Bergmeyer, J. Hao and D.P.J.F.M.E. Schachtman. 2023. Root exudate concentrations of indole-3-acetic acid (IAA) and abscisic acid (ABA) affect maize rhizobacterial communities at specific developmental stages 99:fiad019.

Lu, L., Y. Zhao, M. Li, X. Wang, J. Zhu, L. Liao and J. J. Wang. 2023. Contemporary strategies and approaches for characterizing composition and enhancing biofilm penetration targeting bacterial extracellular polymeric substances.

Majid, M., M. Ali, K. Shahzad, F. Ahmad, R.M. Ikram, M. Ishtiaq, I.A. Alaraidh, A. Al-Hashimi, H.M. Ali and T.S. Zarei. 2020. Mitigation of osmotic stress in cotton for the improvement in growth and yield through inoculation of rhizobacteria and phosphate solubilizing bacteria coated diammonium phosphate 12:10456.

Ming, L., L. Yun and Z. S. Xianglin. 2004. Isolation of endophytic bacteria from cotton and screening of antagonistic bacteria 41:277-282.

Miteu, G.D., A.A. Emmanuel, I. Addeh, O. Ojeokun, T. Olayinka, J. S. Godwin, E.O. Folayan, E.O. Benneth and F. Science. 2023. The Application of Microbial Inoculants as a Green Tool towards Achieving Sustainable Agriculture 2:52-62.

Mitra, S., S.A. Sultana, S.R. Prova, T.M. Uddin, F. Islam, R. Das, F. Nainu, S. Sartini, K. Chidambaram and F.A. Alhumaydhi. 2022. Investigating forthcoming strategies to tackle deadly superbugs: current status and future vision 20:1309-1332.

Muhammad, W., A. Muhammad, T. Mukhtar, A.J. Manan Hamza and Biology. 2022. Comparative efficacy of some new chemistry foliar insecticides against cotton whitefly, Bemisia tabaci (Hemiptera: Aleyrodidae).Online):

Murthy, K.N., K. Soumya, A. Udayashankar, C. Srinivas and S. Jogaiah. 2021. Biocontrol potential of plant growth-promoting rhizobacteria (PGPR) against Ralstonia solanacearum: current and future prospects. p. 153-180. *In* (ed^.) Biocontrol Agents and Secondary Metabolites. Elsevier,

Muthu Narayanan, M., N. Ahmad, P. Shivanand and F.J.M. Metali. 2022. The role of endophytes in combating fungal-and bacterial-induced stress in plants 27:6549.

Naorem, A., S. Jayaraman, Y.P. Dang, R.C. Dalal, N.K. Sinha, C.S. Rao and A. A. Patra. 2023. Soil constraints in an arid environment-challenges, prospects, and implications 13:220.

Pereg, L., M.J. McMillan and Biochemistry. 2015. Scoping the potential uses of beneficial microorganisms for increasing productivity in cotton cropping systems 80:349-358.

Prasanna, R., S. Babu, N. Bidyarani, A. Kumar, S. Triveni, D. Monga, A.K. Mukherjee, S. Kranthi, N. Gokte-Narkhedkar and A.J.E.a. Adak. 2015. Prospecting cyanobacteria-fortified composts as plant growth promoting and biocontrol agents in cotton 51:42-65.

Prasanna, R., B. Ramakrishnan, K. Ranjan, S. Venkatachalam, A. Kanchan, P. Solanki, D. Monga, Y.S. Shivay and S. P. Kranthi. 2016. Microbial inoculants with multifaceted traits suppress Rhizoctonia populations and promote plant growth in cotton 164:11-12):1030-1042.

Qasim, M.J. and A.i.A. Sciences. 2023. Beneficial microbes in plant health: from biocontrol agent to plant growth promoting rhizobacteria 2:39-49.

Ramzan, M., B. Tabassum, I.A. Nasir, A. Khan, M. Tariq, M.F. Awan, N. Shahid, A.Q. Rao, M.U. Bhatti, N.J.B. Toufiq and B. Equipment. 2016. Identification and application of biocontrol agents against Cotton leaf curl virus disease in Gossypium hirsutum under greenhouse conditions 30:469-478.

Romero-Perdomo, F., I. Beltrán, J. Mendoza-Labrador, G. Estrada-Bonilla and R.S. Bonilla. 2021. Phosphorus nutrition and growth of cotton plants inoculated with growth-promoting bacteria under low phosphate availability 4:618425.

Rowlett, V.W., V.K. Mallampalli, A. Karlstaedt, W. Dowhan, H. Taegtmeyer, W. Margolin and H.J.J.o.b. Vitrac. 2017. Impact of membrane phospholipid alterations in Escherichia coli on cellular function and bacterial stress adaptation. 199(13):10.1128/jb. 00849-00816.

Sahu, B., J. Singh, G. Shankar and A.J.I.J.o.C.S. Pradhan. 2018. Pseudomonas fluorescens PGPR bacteria as well as biocontrol agent: A review 6:01-07.

Sampathkumar, A., K.E.A. Aiyanathan, S. Nakkeeran and S.J.B.C. Manickam. 2023. Multifaceted Bacillus spp. for the management of cotton bacterial blight caused by Xanthomonas citri pv. malvacearum 177:105111.

Sharath, S., S. Triveni, Y. Nagaraju, P. Latha and B.J.F.i.A. Vidyasagar. 2021. The role of phyllosphere bacteria in improving cotton growth and yield under drought conditions 3:680466.

Siddiqui, Z.A.J.P.b. and biofertilization. 2006. PGPR: prospective biocontrol agents of plant pathogens 111-142.

Stringlis, I.A., R. De Jonge, C.M.J.P. Pieterse and C. Physiology. 2019. The age of coumarins in plant–microbe interactions 60:1405-1419.

Su, Z., G. Liu, X. Liu, S. Li, X. Lu, P. Wang, W. Zhao, X. Zhang, L. Dong and Y.J.C. Qu. 2023. Functional Analyses of the Bacillus velezensis HMB26553 Genome Provide Evidence That Its Genes Are Potentially Related to the Promotion of Plant Growth and Prevention of Cotton Rhizoctonia Damping-Off. 12:1301.

Thiruvengadam, R., K. Gandhi, S. Vaithiyanathan, H. Sankarasubramanian, K. Loganathan, R. Lingan, V.R. Rajagopalan, R. Muthurajan, J. Ebenezer Iyadurai and P.J.I.J.o.M.S. Kuppusami. 2022. Complete genome sequence analysis of Bacillus subtilis Bbv57, a promising biocontrol agent against phytopathogens 23:9732.

Vesga, P., E. Augustiny, C. Keel, M. Maurhofer and J.J.E.M. Vacheron. 2021. Phylogenetically closely related pseudomonads isolated from arthropods exhibit differential insect-killing abilities and genetic variations in insecticidal factors 23:5378-5394.

Wu, Z., H. Yue, J. Lu, C.J.W.J.o.M. Li and Biotechnology. 2012. Characterization of rhizobacterial strain Rs-2 with ACC deaminase activity and its performance in promoting cotton growth under salinity stress 28:2383-2393.

Xiang, N., K.S. Lawrence, J.W. Kloepper, P.A. Donald, J.A. McInroy and G.W.J.P.D. Lawrence. 2017.sBiological control of Meloidogyne incognita by spore-forming plant growth-promoting rhizobacteria on cotton 101:774-784.

Yasmin, S., F.Y. Hafeez, M. Schmid and A.J.P.J.B. Hartmann. 2013. Plant-beneficial rhizobacteria for sustainable increased yield of cotton with reduced level of chemical fertilizers 45:655-662.

Yu, Y., Y. Gui, Z. Li, C. Jiang, J. Guo and D.J.P. Niu. 2022. Induced systemic resistance for improving plant immunity by beneficial microbes 11:386.

Zebelo, S., Y. Song, J.W. Kloepper, H.J.P. Fadamiro, Cell and Environment. 2016. Rhizobacteria activates (+)-δ-cadinene synthase genes and induces systemic resistance in cotton against beet armyworm (Spodoptera exigua) 39:935-943.

Zhang, L., Y. Wang, S. Lei, H. Zhang, Z. Liu, J. Yang and Q.J.B.m. Niu.2023. Effect of volatile compounds produced by the cotton endophytic bacterial strain Bacillus sp. T6 against Verticillium wilt 23:8.

Zhou, B., R. Jia, X. Chen, L. Yang, M. Duan, F. Xiao, C. Liang, D. Zhou, W. Li and C.J.A.W.M. Liu. 2023. Impact of bacteria-nitrogen coupling on cotton growth and nitrogen utilization under different salt stress 280:108221.