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REVIEW ARTICLE

Harnessing the potential of beneficial microbes of *Rauvolfia* species in sustainable agricultural practices: A Review

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Abstract

The widespread utilization of agrochemicals and chemical fertilizers in agriculture that were initially embraced to address agricultural expansion to feed growing world population, have led to significant environmental and health challenges including agrochemical poisoning, unintentional acute pesticide poisoning (UAPP), air and soil pollution, that damage ecosystems and human health. It causes disruption of the soil microbiome and also that of aquatic ecosystems through eutrophication, and human health via complex food webs. Hence, these problems underscore the urgent need for more sustainable agricultural practices. Biofertilizers or microbial inoculants are presented as promising substitutes to chemical fertilizers. Formulations of biofertilizers exploit the beneficial physiological attributes of microbes dwelling in the rhizosphere that may sometimes also invade the interior of plants, like *Rauvolfia serpentina* (Sarpagandha). The beneficial attributes of these microbes include production of indole-3-acetic acid (IAA), solubilization of phosphate, ACC deaminase activity, siderophore release, and antagonistic activity against pathogens. These qualities make them effective in enhancing plant growth, phytopathogen control, and they also have efficient colonizing ability. Promoting the use of biofertilizers is advocated as a dual solution: addressing the global challenge of feeding a growing population while safeguarding environmental health in a sustainable manner. This shift away from agrochemicals is seen crucial for achieving food security and safety, aligning with Sustainable Development Goals (SDGs) 2030.

Keywords: *Rauvolfia*, Rhizobacteria, PGPR, Endophytes, Sustainable agriculture, Biofertilizers.

Introduction

Soil microbial diversity is essential for ecosystem functioning to ensure continuous food supply. However, the disproportionate use of chemical fertilizers causes fluctuations in the microbial diversity inhabiting the soil causing agrochemical poisoning and unintentional acute pesticide poisoning (UAPP). This also leads to the washing away of toxic agrochemicals and have polluted the soil and water bodies and when they enter the food chain, they threaten the health of human beings and different animal groups, and also leads to the progression of pest resistance. The agrochemicals and their degradation products have set an alarm bell because of their harmful repurcussions on the health of human beings because they are neurotoxic, carcinogenic and also cause developmental toxicity (teratogenicity) and disorders of the reproductive system like endometriosis, PCOS, etc. (Punia *et al.,* 2023). Therefore, our unconditional dependence and usage of agrochemicals, to augment production of food is laden with two genuine concerns – soil ecological imbalance and utter limitation of resources to the plant. Howevere, the difficulty in assessing the negative impacts of agrochemicals on soil microbial diversity poses difficulty, because no more than 1% of the bacterial species are culturable.

Lorenz Hiltner, a German agronomist and plant physiologist in 1904 coined the term rhizosphere and since then rhizosphere ecology and later rhizosphere engineering have become the subjects of extensive research. Rhizosphere is the zone of soil directly influenced by the roots of plants and this zone is considered critical because it is the host to

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an enormous diversity of microbes encompassing bacteria, fungi etc.It needs to be emphasized that the roots significantly impact the diversity of microbial community that are closer to them in comparison to those further away. The microbial communities play a vital role in the physiological functioning of plants, and a few of them penetrate and multiply inside the plants, functioning as endophytes. Among the interacting microbes, the beneficial bacteria exert numerous health benefits on the plant and they are popularly known as plant growth promoting rhizobacteria (PGPR). Their functional role is to accentuate growth of herbs and trees by causing morphological changes, enhanced metabolite production, mitigation of salinity stress, antioxidant properties and phytopathogen control (Kumar *et al.,* 2017, Singh *et al.,* 2021). Hence, it is hypothesized that manipulating the diversity of microbes (number and distribution pattern) in the soil can improve agricultural output. This surmise finds application in making formulations of biofertilzers or microbial inoculants that are ecofriendly and sustainable replacements to chemical fertilizers. Figure 1 highlights the detrimental effects of chemical fertilizers and also the advantages of beneficial bacteria (PGPR and endophytes) in augmenting growth of plants.

The use of herbal medicines or phytomedicines for combating diseases and human suffering is as old as civilization and their therapeutic properties are attributed to certain metabolites like alkaloids, phenolics (simple phenolics and flavonoids) also referred to as secondary products or secondary metabolites, glycosides and their derivatives, in addition to polysaccharides, waxes and fatty acids. These metabolites are crucial for plant survival because they aid in deterring pests, attracting pollinators and facilitate survival of the species by antioxidant action, scavenging of free radicals, indirect signaling of reactive oxygen species, absorption of ultraviolet light, in addition to deterring pathogenic microorganisms. Interestingly, in various plants like *Catharanthus*, *Hypericum perforatum*, *Artemisia annua*, *Rauvolfia tetraphylla*, *Solanum nigrum*, and *Achillea fragrantissima,* stress conditions have stimulatory effect on the level of secondary metabolites (Saleem *et al.,* 2022). Researches have shown that the level of these phytochemicals can be impacted by manipulating the microbiome diversity in the soil (Schütz *et al.,* 2021).

The genus *Rauvolfia* Plum. ex L. bears long tapering snake-like roots and it was named so to honour Dr. Leonhard Rauwolf, a German physician of 16th century who studied lots of plants while traveling to India. *Rauvolfia serpentina* (L.) *Benth. ex Kurz,* commonly known as Sarpagandha finds mention in the Charaka Samhita (c 700 BC) and found application in Ayurvedic and Unani medicines for the treatment of snake bites. Rustom Jal Vakil, an Indian physician is credited with introducing *Rauvolfia serpentina* to Western medicine and in 1949 he published a seminal paper in the British Medical Journal that highlighted the plant's potential for treating hypertension. Ever since this publication, the plant gained immense popularity from the academic fraternity and also the pharmaceutical industry (Lobay, 2015). Besides this, the rhizosphere of *Rauvolfia* is the home to several plant growth promoting rhizobacteria. This review article is aimed at highlighing the recent progress in the understanding and applications of these bacteria in sustainable agricultural systems.

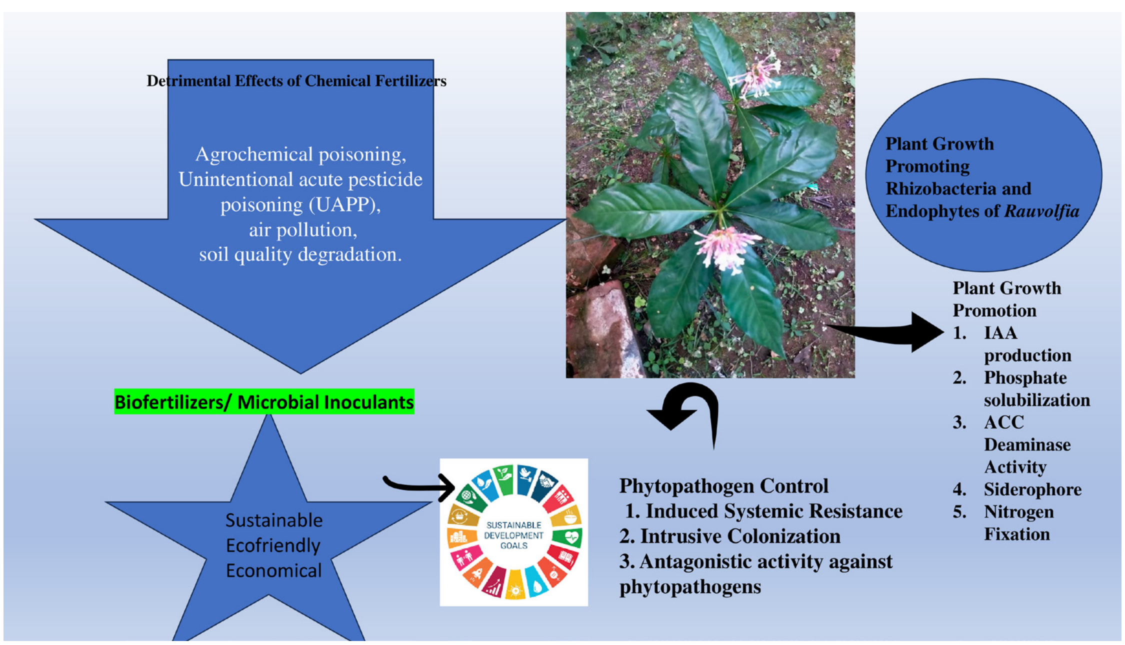

Figure 1: The schematics depict the disadvantages of chemical fertilizers and it also highlights the functional attributes of beneficial bacteria (PGPR and endophytes)

The Genus Rauvolfia – Distribution, Phytochemicals and Medicinal Uses

Rauvolfia is a diverse genus within the Apocynaceae (also called the dogbane/ milkweed family), encompassing numerous species distributed across different continents. Its medicinal properties and ecological roles make it an important subject of study in botany, pharmacology, and conservation biology. In some regions, *Rauvolfia* plants are referred to as "devil peppers," likely due to local folklore or traditional beliefs associated with their appearance or properties. The plants are distributed worldwide with 131 species that grow in wild conditions in America, Africa, and South East Asian countries. Of these five species namely *R. serpentina* Benth. ex Kurz., *R. hookeri* SR Sriniv. & Chithra, *R. verticillata* (Lour.) Baill., *R. micrantha* Hook f and *R. tetraphylla* L. (*R. canescens* L) are reported from the areas of Gangetic plains, sub-Himalayan tracts, covering Shimla to Assam, Nepal and Bhutan and tracks of Western Ghats. The plants are evergreen undershrubs reaching 60-90cm in height and bear small flowers in pale whitish to reddish violet hues (Gantait *et al.,* 2023).

R. serpentina and *R. vomitoria* mostly find application in the treatment of several maladies, because they contain alkaloids like ajmaline, ajmalicine, serpentine, yohimbine and reserpine, which are collectively referred to as monoterpene indole alkaloids (MIAs) (Mukherjee *et al.,* 2019). Herbal extracts from *Rauvolfia* have confirmed their antibacterial, antioxidant and cardioprotective properties, besides having inhibitory cholinesterase and antihepatotoxicity functionalities. Clinical trials of these formulations have proven their roles in treating diseases of the heart and central nervous system and they are, also useful in the treatment of high blood pressure, diabetes and psoriasis (Kumar *et al.,* 2022). A recent discovery by Fadaeinasab *et al.,* 2020 of a unique alkaloid - Reflexin A, from *Rauvolfia reflexa* highlighted its role in colorectal cancer cells' apoptosis.

Pharmaceutical industry has been exploiting *Rauvolfia serpentina* since long for making antihypertensive drugs because of its ability to deplete catecholamine (Maurya *et al.,* 2023). Ayurveda and medicines of the Unani systems also mention the uses of *Rauvolfia* in the treatment of snake bites, hypertension, anxiety, schizophrenia and also in the treatment of *Plasmodium* infections, stomach pain, dysentery, insomnia etc. Its uses as a uterine stimulant (uterotonics), antipyretic, antipsychotic drug and tranquilizer are also known.

The reports by Chen *et al.* (2022) have highlighted that the extracts of *Rauvolfia vomitoria* and *Pao Pereira* were inhibitory to cancer stem cells in ovarian cancers *in-vitro* condition. Besides this, *in-silico* studies have revealed that alkaloids of *Rauvolfia serpentina* can lower down biosynthesis of cholesterol and so they could be potential leads in the treatment of high cholesterol (Azmi *et al.,* 2021). Additionally, reserpine can generate hightened antibiofilm response in the urinary catheter model and so it can be combined with other commercial antibiotics and used as an improved therapeutic formulation (Parai *et al.,* 2020). The importance of a structured database on plant-derived molecules was needed. Realizing this, a database Serpentina DB has been created by Pathania *et al.* (2015) and it contained a collection of 147 plant-based molecules classified on the surmise of their chemistry, source of plant part, and their three-dimensional structures. This has provided a solid foundation for computational and experimental studies aimed at identifying and developing novel therapeutic agents and also as a promising tools for researchers engaged in rational drug design, particularly in the search for aldose reductase inhibitors for managing diabetes-related complications.

Biotechnological Approaches for Improvement and Conservation of Rauvolfia

Propagation through seeds in *Rauvolfia* is poor because it suffers from several pitfalls like lowered seed set, poor germination rates and elevated chances of genetic variations. Since these compromise with the quality and quantity of secondary metabolites, attention is now shifting towards alginate encapsulated shoot tips and they are considered promising alternatives for short- to mid-term storage, germplasm transfer, and *in vitro* propagation for *Rauvolfia* sp. Researches have also focussed on studies to understand how the encapsulating agent, levels of substrate and matrix are important determinants of the germination potential and genetic uniformity of tissue culture generated *R. serpentina* shoot tips (Gantait *et al.,* 2017). Recently, tissue culture has enabled the regeneration of plants through callus, or formation of somatic embryos, artificial seed or culture of hairy roots and induction of polyploidy and their clonal fidelity has been validated by the use of molecular markers and genetic transformation (Mukherjee *et al.,* 2019). Advances in biotechnology are expected to facilitate the modification of alkaloid content and enhance the accumulation of various alkaloid classes through the use of elicitors (Carréra *et al*. 2022).

Plant Growth Promoting Rhizobacteria (PGPR) of Rauvolfia

The rhizosphere comprises of three distinct zones - the endorhizosphere, the rhizoplane, and the ectorhizosphere and the microbes residing in these regions produce substances that promote overall morphology of plants (Bhattacharya and Jha, 2012). According to Berendsen *et al.,* 2012, plant growth is tremendously affected by the microbiome present in the rhizosphere, and therefore, they are also called the second genome of plants. Effects exerted by the rhizospheric microorganisms encompasses the rhizosphere cross talk and can be positive, negative to no effects at all (Wu *et al.,* 2023). In turn, roots exudates consist of photosyntheticaly fixed carbon and also other biomolecules such as hydrates of carbon(carbohydrates), organic acids, phenolics and flavonoids and auxins and they play immense role in reshaping the microbiome. The rhizomicrobiome is itself determined by the physicochemical properties of the soil, genotype of the plant and the biochemical attributes of root exudates.

Kloepper and Schroth first introduced the term PGPR in 1980 and earlier in 1978 during the IVth International Congress of Bacterial Plant Pathogens held in France, where they highlighted the significance of rhizobacteria for enhancing plant health and growth (Goswami *et al.* 2016). Nowadays, PGPR are becoming popular in agriculture as replacements to agrochemicals. Certain specific strains of rhizobacteria are applied to crops and medicinal plants and they improve metabolite production, growth and yield. In addition to boosting biomass production, they improve nutrient uptake and soil fertility. They also facilitate plants in overcoming the impact of abiotic stress (Vaghela and Gohel, 2022). Besides, these rhizobacteria endow their host plants with benefits such as medicinal properties and enhanced bioactive compound production. It is therefore expected that the use of PGPR as microbial inoculants will ensure conservation of medicinal plants that are rare and endangered (Chanda *et al.,* 2023). The isolation and identification of specific strains of rhizobacteria including *Azotobacter*, *Acinetobacter*, *Bacillus*, *Brevibacterium*, *Burkholderia*, *Exiguobacterium*, *Pseudomonas*, *Pantoea*, *Mycobacterium*, *Methylobac-terium*, and *Serratia* from medicinal plants have become a promising area of research.

PGPR inoculants are therefore important drivers of sustainable and environment-friendly agricultural practices. In order to provide an all inclusive and relevance of this upcoming area of beneficial microbes in sustainable agriculture a bibliometric study was carried out using the Dimensions database. In this database, a search using two key words "beneficial microbes" and "sustainability" in the last 10 years (from 2014-2024) yielded 11,817 publications with 929 patents and 153 policy documents.

The application of microbial inoculants containing desirable bacteria to agricultural crops has shown promising results in the lab and also in the green house conditions.The application of microbial inoculants can mitigate the negative environmental impacts incurred due to enhanced use of agrochemicals and their application to crops has shown promising results in the lab and also in the green-house conditions. Understanding pathways and interactions of PGPR can help researchers optimize their application for better agricultural outcomes.

Two types of effects are observed by the application of PGPR:

Plant Growth Promotion

The functional roles of rhizobacteria including the release of indole-3-acetic acid (IAA), solubilization of phosphate, ACC deaminase activity, and siderophore production help in enhancing growth of plants. Specifically, role played by IAA including promotion of cell division and their elongation, differentiation, flowering, and formation of lateral roots and this facilitates growth and development of plants. PSB also referred to as phosphate solubilizing bacteria facilitate solubilization of phosphate and also in mobilizing organic phosphorus in phosphorus acids, and ligands. Recent years have witnessed, that PGPR studies tend to focus primarily on plant agronomic parameters (like growth rate, yield and biomass) and the nitrogen content of the plant, while other crucial aspects like phosphorus (P) fertilization levels, its solubilization and uptake by the plants are often overlooked. The production of enzyme ACC deaminase (1-aminocyclopropane-1-carboxylate deaminase) which is crucial for regulating the endogenous ethylene concentration in young seedlings by PGPR has also been realized and it helps in catalyzing the change of ACC to ammonia and alpha-ketobutyrate. This conversion enhances growth of plants which is thought to be mediated by reducing ethyne concentration (Shahzad *et al*. 2013). By carefully understanding and harnessing these mechanisms, it is possible to enhance growth of plants effectively by the application of PGPR. This approach can significantly reduce the reliance on chemical fertilizers and pesticides, thereby mitigating the negative environmental impacts associated with their excessive use.

Phytopathogen Control

Quick and intrusive colonization by PGPR makes them excellent biocontrol agents by effectively preventing detrimental pathogens like *Fusarium oxysporum* from invading plant roots. Interestingly, some PGPR produce a rhizosheath around the roots, protects them from dessication and helps them in combating stress incurred in arid conditions (Naseem *et al.,* 2018). Additionally, PGPR produce various antibiotics such as 2,4-diacetylphloroglucinol, phenazine-1-carboxylic acid, oomycin, pyrrolnitrin, pyoluteorin, zwittermicin A, pantocin, and kanosamine, which have broad-spectrum activity against phytopathogens. These antagonistic rhizobacteria also produce siderophores, which are essential for metal sequestration. According to Annapurna *et al.,* 2012 certain PGPR like *Pseudomonas putida, Serratia marcesans, Bacillus pumilus and Flavimonas oryzihabitans,* display elevated defensive capacities against subsequent biotic challenges through Induced Systemic Resistance (ISR) and this feature provides an additional layer of defense against pathogens and thus alleviating the need for chemical pesticides. Therefore, promoting the use of PGPR based biofertilizers to agricultural crops can provide dual benefit to plants – (i) enhanced plant growth and (ii) reduced reliance on chemical fertilizers and pesticides. Indeed, enhanced research in these technologies and their applications will contribute to sustainable agricultural systems and also help in the identification of novel bacteria like *Delftia tsuruhatensis* that can be useful in agriculture.

Delftia tsuruhatensis - unique rhizobacterium with PGPR properties

The isolation of *Delftia tsuruhatensis* was first reported from sludge in Japan in 2003. This strain was Gram-negative, aerobic, motile, and did not form spores. The genus was ascribed to the the family Comamonadaceae and it has a single species *tsuruhatensis* that was a predominant genera rhizosphere soil, activated sludge, and polluted environment. Further, *Delftia tsuruhatensis* with PGPR properties isolated from the rhizosphere of *Rauvolfia serpentina* (L.) Benth. ex Kurz, was capable of inhibiting fungal pathogens and also overcoming limiting iron concentration in the soil due to siderophore production (Prasannakumar *et al*. 2015b).

Iron is an important constituent of coenzymes that play an important role in energy transformation processes like photosynthesis, respiration and nitrogen fixation. PGPR also release siderophores, that help in scavenging iron from soil under iron-limiting conditions. Once siderophore-iron complex is formed, it is transported back into the microbial cell where iron is released and utilized. As the discovery of siderophores continues many of them are characterized, although a lot many still remain to be discovered. Mostly species of *Pseudomonas* including *P. fluorescens* and *P. aeruginosa* are important siderophore producers. Their molecular weight is less than 1kDa and they contain the functional groups like hydroximates and catechols, that facilitate optimal binding of iron (Goswami *et al.,* 2016). Another isolate HR 4 of *Delftia tsuruhatensis* was isolated from rice in China, and *in vitro* studies demonstrated its ability to inhibit the pathogens *Xanthomonas oryzae* pv. *oryzae*, *Rhizoctonia solani* and *Pyricularia oryzae* Cavara that infested rice (Han *et al.,* 2005). Molecular studies in *Delftia* revealed that it carried genes associated with adaptation in the rhizosphere and this feature made it a promising rhizobacterial strain for use in sustainable agriculture systems. Genome annotation revealed that it carried genes responsible for secondary metabolism, carbohydrate active enzymes (CAZymes), and phosphate transporter genes (Yin *et al.,* 2022). The genus *Delftia* along with *Pseudomonas aeruginosa* were also used as analgesic and antipyretic in wastewater treatment plant and they also brought about degradation of acetaminophen (APAP) using membrane bioreactor (Gusseme *et al.,* 2011). Later, the metabolic characterization of *Delftia* was done and it was revealed that it had the ability for the degradation of low molecular weight phenolic compounds(Juárez-Jiménez *et al.,* 2010).

Biofilms are known to be responsible for MDR and biofilm formation can be prevented by the inhibition of quorum sensing. From the rhizosphere of *Cyperus laevigatus, Delftia tsuruhatensis* SJ01 was isolated *and* it showed QSI activity against *Chromobacterium violaceum* CV026 (Singh *et al.,* 2017). Thereafter, it was also reported as an emergent opportunistic pathogen in immunocompromised patients and caused pneumonia in a minor who had undergone cardiac surgery (Ranc *et al.,* 2018). From the rhizosphere of tobacco, *D. tsuruhatensis* MTQ3, another PGPR strain with antimicrobial activity was isolated (Hou *et al.,* 2015).

The diversity of PGPR have highlighted complex interactions among and between these bacteria and plants. Different PGPR strains can adapt to various environmental conditions, enhancing their ability to colonize and exert beneficial effects on plant roots. Ongoing research and field trials are crucial for optimizing the use of PGPR in different crops and environmental conditions. Understanding PGPR diversity in Rauvolfia and their mechanism of action will pave the way for development of microbial inoculants that are more reliable and sustainable. The most predominant rhizobacteria found in the rhizospheres of *Rauvolfia* species in the Western Ghats (WG) regions have shown significant potential as Plant Growth-Promoting Rhizobacteria (PGPR). These bacteria can serve as effective biofertilizers and biopesticides, contributing to sustainable agricultural practices (Prasannakumar *et al.,* 2013a). In this context, *Paenibacillus sp. S-12,* is a promising rhizospheric bacteria isolated from *Rauvolfia serpentina* in Ranchi, India and its genome annotation has revealed its survival ability under varied environmental settings. This adaptability suggests potential applications in agriculture, especially as a probiotic for plants, which can enhance plant health and growth (Singh *et al*, 2023). Certain phosphate solubilizing bacteria improved seed germination of *Rauvolfia tetraphylla* when grown in a media comprising of red soil, sand, vermicompost, and *Rhizobium* (Kademani *et al.,* 2017).

The following Table 1 provides list of beneficial rhizospheric and endophytic bacteria and fungal strains from *Rauvolfia* and their PGPR properties.

Sustainable cultivation of medicinal plants by applying PGPR inoculants are expected to curb diseases such as root rots, leaf blights and spots, bacterial galls, soft rots, and nematode root knot. Additionally, careful manipulation of plant microbe interaction in medicinal plants can help in improving amount of phytochemicals. Certain genera like *Pseudomonas*, *Azospirillum*, *Azotobacter*, *Bacillus*, *Burkholderia*, *Enterobacter*, *Rhizobium*, *Erwinia*, *Mycobacterium*, *Mesorhizobium*, *Flavobacterium*, *Klebsiella*, *Alcaligenes*, *Arthrobacter* and *Serratia* display several PGPR activities including siderophore production, nitrogen fixation, removal of heavy metals, production of antifungal compounds etc. The control of phytopathogens is also exerted by blocking expression of genes responsible for virulence in the pathogen (Singh and Pathak, 2015).

Future Prospectives

The rich biodiversity in tropical countries like India coupled with varied environmental conditions lead to co-evolution

Table 1: List of beneficial rhizospheric and endophytic bacterial/ fungal strains from *Rauvolfia* and their PGPR properties

Bacterial/ Fungal Strains	*Source Plant*	*Rhizosphere/ Endophyte*	*PGPR Properties*	*Reference*
Paenibacillus sp. S 12	*Rauvolfia serpentina*	Rhizosphere	CAZymes, probiotic, and stress-protected genes	Singh *et al.,* 2023
Pseudomonas aeruginosa RAU 305	*Rauvolfia* serpentina	Endophyte	Antimicrobial	Pal and Paul, 2020
Delftia tsuruhatensis WGR–UOM–BT1	*Rauvolfia* serpentina	Rhizosphere	Suppression of fungal phytopathogens, IAA production, phosphate solubilization, ACC deaminase activity	Prasannakumar *et al.,* 2015b
Pseudomonas, Methylobacterium and Bacillus	Different *Rauvolfia* species	Rhizosphere	IAA production, phosphate solubilization, production of siderophore, salicylic acid, HCN, phytase and protease except the production of chitinase and cellulase with highest root colonizing ability and antagonistic activity against F. oxysporum and A. flavus.	Prasannakumar *et al.,* 2013 a
Penicillium citrinum Aspergillus niger, Penicillium citrinum, Cladosporium sp., Curvularia lunata, Aspergillus sp., Alternaria sp. and Aspergillus fumigatus	*Rauvolfia* serpentina	Endophyte	Antibacterial bioactive compounds	Sahu *et al.,* 2016
Fusarium sp., Phomopsis sp., Colletotrichum sp., Cladosporium sp., Aspergillus sp., Xylaria sp., Alterneria sp. and Gleomastix sp	*Rauvolfia* serpentina	Endophyte	Antibacterial activity against human pathogens	Singh *et al.,* 2016
Alternaria sp	*Rauvolfia tetraphylla root*	Endophyte	Antibacterial, antioxidant and antimitotic activities	Hemashekhar *et al.,* 2019
Alternaria sp. RL4	*Rauvolfia* serpentina aerial parts	Endophyte	Antibacterial potentials, source of bioactive compounds	Ghosh *et al.,* 2018
Colletotrichum gloeosporioides, *Penicillium* sp. and *Aspergillus awamori*	*Rauvolfia serpentina*	Endophyte	Hypocholesterolemic, antimicrobials and antioxidant (pharmaceutical value)	Nath *et al.,* 2015

of plants and microbes. The rhizosphere of each plant hosts a unique microbiome and some microbes also occur as endophytes – together they exert immense effect on growth and development, synthesis of bioactive compounds and also the overall plant health. These, beneficial interactions improve resilience of plants against phytopathogens in addition to providing required minerals and nutrients to plants. In addition to the variations in the microclimatic conditions, the diversity of microbes in the rhizosphere is also fine tuned by the phenology of plants, their metabolic and physiological responses, in addition to their chemical profile, and overall morphology. These attributes are considered to be dynamic and boost the immunity of plant systems by enabling them to better withstand environmental stresses (Giri *et al.,* 2022).

The objective of realizing sustainable food production systems by 2030 seems topmost priority and for achieving this, the integration of microbe-mediated approaches into agricultural practices is a pressing priority. Accomplishing these objectives by 2030 as envisioned in SDGs– particularly concerning food production, biodiversity loss, ecosystem services, and agroecosystem stability requires a paradigm shift towards agricultural practices that address environmental concerns. It is expected that microbe-mediated sources can improve soil health, nutrient cycling and improve plant resilience to stress and can help in developing sustainable agriculture systems. By leveraging on microbial interactions farmers can reduce dependance on synthetic inputs such as fertilizers and pesticides, hence promoting sustainable agriculture while mitigating environmental impacts. Sustainable agricultural systems utilizing PGPR are emerging as potential substitutes to chemical fertilizers. Hence, to accomplish long term sustainability and flexibility amidst growing environmental challenges, the adoption of holistic approaches will require a vision encompassing sustainable agricultural practices. The adoption of integrated cropping practices strengthens agricultural systems against climatic fluctuations, enhances soil health and also counters biodiversity loss. PGPR technologies can reinforce regenerative agricultural perspectives, while reducing the need for agricultural inputs and help in achieving food security in sustainable manner.

While research into rhizobacteria and endophytic microbes is supported by government policies and funding, it is essential to provide incentives and knowledge to farmers to encourage adoption of these technologies. This support is essential for reducing reliance on harmful agrochemicals and promoting sustainable agricultural practices that enhance productivity without compromising environmental and human health. Medicinal plants like *Rauvolfia* are host to numerous beneficial microbial counterparts in the rhizosphere and also within the plants. Although, many secondary metabolites produced by them have been capitalized by the pharma industry to produce herbal drugs, it is expected that cryptic metabolic pathways exist, and some of them have remained silent within an organism's genome until activated under certain conditions. They might encode for the production of novel bioactive compounds that could have significant therapeutic value. These cryptic metabolic pathways can be unveiled by Next Generation Sequencing (NGS) technologies coupled with genome mining. It might however be challenging to identify and explore the conditions in which they are activated. The progress made in understanding genomic and metabolic landscapes of plants yielding herbal medicines and the beneficial microbiota associated with them, is expected to help in the development of novel therapeutics to address unmet medical needs of the society besides addressing sustainable agriculture by the development and adoption of microbial inoculants/ biofertilizers. Hence, the use of biofertilizers represents a shift towards sustainable agriculture, offering a viable solution to current agricultural challenges while contributing to broader global sustainability goals.

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