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Microbial Mechanisms Suppressing Invasive Weeds for Sustainable Agriculture: A Review

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Abstract— *Invasive weeds are serious problems in crop production. They affect the production of vital crops, such as wheat, rice, sorghum, maize, and legumes. Weeds are major biotic stressors that reduce biomass and yield in many crops. Parthenium hysterophorus, Lantana camara, Chromolaena odorata, and Ageratum conyzoides are the predominant weed species that threaten agricultural fields in India. These aggressive weed species compete with other crop plants for vital resources such as growth factors, water, essential nutrients, and space, and ultimately cause a remarkable loss of agricultural yield. Furthermore, weed plants release allelopathic compounds in soil that inhibit seed germination and crop growth, and also alter soil pH. Farmers traditionally rely on weed management practices that demand excessive labour and high costs while delivering low efficiency. Although chemical herbicides are effective in controlling weeds, excessive application poses severe environmental risks, and repeated long-term use may cause weed resistance. Considering the secondary effects of chemical herbicides, rhizobacterial biological weed control is an efficacious alternative to control these weed plants. Increasing agricultural yields is essential to meet the food needs of a rapidly growing global population. Numerous rhizobacteria have been identified for their ability to suppress weed growth. The use of rhizobacteria is a new and upcoming approach for the biocontrol of invasive weeds. Certain rhizobacterial strains suppress weed growth, providing crop plants with a competitive advantage for essential growth factors. Various mechanisms have been studied by which rhizobacteria can suppress weed growth, production of plant growth regulators (indole-3-acetic acid and 5-aminolevulinic acid), antibiotics, VOCs (hydrogen cyanide), exopolysaccharides (biofilm), and phytotoxins. Inoculation of potent rhizobacterial strains, which show the property of biocontrol of weeds, can be used for the management of weeds and can be implemented in sustainable agriculture practices. Use of rhizobacteria is an environment friendly approach for the management of invasive weeds and is highly compatible with sustainable agriculture.*

Keywords— ***Allelopathy, Biocontrol, Invasive weeds, Weed suppression, Rhizobacteria***

I. INTRODUCTION

In India, invasive weeds pose a serious problem in agricultural fields for the production of crops, as they compete with other crops for growth factors, resulting in yield losses. Because of their quick spreading ability, the fierce competition nature invasive weed species have become a major threat to soil health and agricultural sustainability. For instance, invasions made by weeds such as *Parthenium hysterophorus, Lantana camara, Chromolaena odorata*, and *Ageratum conyzoides* inhibit crop growth on a large scale by releasing allelopathic compounds. The impact of this invasion results in inhibition of seed germination and reduces crop productivity, as well as strongly competing for vital resources like nutrients, water, CO2, and light (Kohli et al., 2006; Phukan et al., 2021). Several control strategies, including cultural, manual, and mechanical methods, have been implemented in response to the harmful impacts of invasive weeds;

however, these methods are less effective, costly, and laborious (Phukan et al., 2021; Rao, 2000). The use of herbicides is a common and less costly way of managing invasive weeds. It has become the most popular because of its practicality and rapid results, but it also has adverse environmental effects. The excess use of herbicides can result in harmful herbicide residues, pollution, and ecological disruption. It may also create a weed resistant to a certain herbicide.

Invasive weeds influence soil ecosystems by disrupting nutrient cycling, altering soil pH, diminishing organic matter quality, and modifying microbial community composition, and often supporting microbial groups associated with the invader at the expense of beneficial microorganisms such as PGPR (Stefanowicz et al., 2019). Invasive weeds can cause serious health hazards to humans and cattle, making them hazardous weeds in India (Kaur et al., 2014). For instance, *P. hysterophorus* can reduce crop production by up to 40–90% of total crop yield reduction of sorghum, wheat, maize, and legumes. *Lantana camara* can lower soil fertility by altering the microbial balance and increasing the phenolic content of the soil. These impacts highlight how invasive weeds threaten agriculture in India by reducing crop yields and disrupting soil quality. Considering all the possible outcomes of using herbicides for weed management, there is a need to develop an effective weed management practice that will minimize reliance on chemical herbicides. For that purpose, the biological weed control may become an effective option to control weed plants. The use of rhizobacteria is one such biological approach to control weeds.

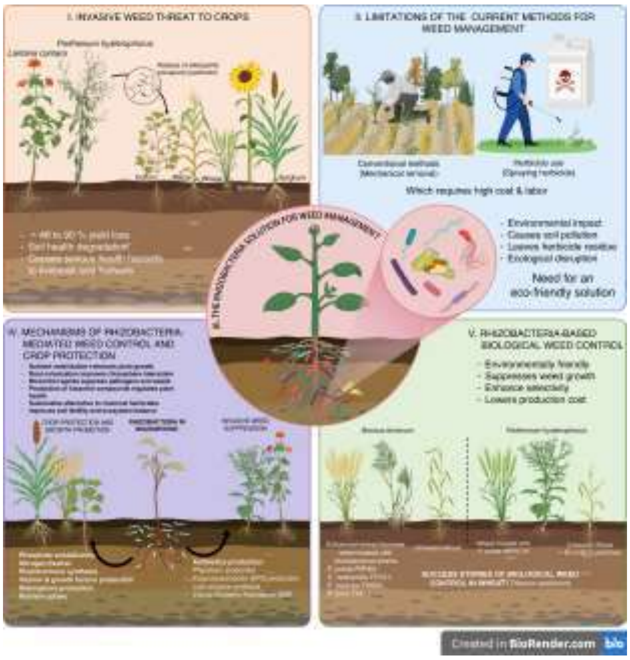

Fig. 1. Rhizobacteria-Mediated Mechanisms for Sustainable Weed Management and Crop Protection

Rhizobacteria are beneficial microbes that colonize in diverse parts of plant roots, including the rhizosphere, rhizoplane, and endorhizal bacteria. The rhizosphere is a zone of highest microbial activity, resulting in an enclosed nutrient pool that includes macro and micronutrients, which are available due to the accumulation of plant debris, like leaves, fruits, and twigs, which provide a source of energy and nutrients such as sugars and amino acids (Gray & Smith, 2005). The number of microbes in the rhizosphere, which is greater than that found in the surrounding bulk soil due to the increased availability of nutrients, makes this phenomenon evident (Weller & Thomashow, 1994). Depending on how rhizobacteria influence plant growth, rhizobacteria can be categorised into three categories: beneficial, harmful, and neutral (Dobbelaere et al., 2003).

Based on their mode of action and their effect on the plant, the rhizobacteria are classified into two categories: Plant Growth-Promoting Rhizobacteria (PGPR) and Deleterious Rhizobacteria (DRB) (Nehl et al., 1997; Phukan et al., 2021). PGPR, may also be referred to as yield-increasing bacteria (YIB), are non-infectious beneficial microbes that enhance plant growth through multiple mechanisms, such as phytohormone synthesis, nutrient uptake, and induce disease resistance in the host plant by producing antagonistic substances against pathogens (R. J. Kremer et al., 2006; Phukan et al., 2021). In contrast, pathogenic microbes, called deleterious rhizobacteria (DRB), disrupt root development, reducing plant growth and yield. These microbes are also referred to as yield decline (YD) bacteria (Phukan et al., 2021). Rhizobacteria can work as PGPR through direct mechanisms, positively affecting plant growth and development. PGPR can enhance plant growth through several key mechanisms, including fixing nitrogen, solubilizing phosphorus, producing growth hormones, and suppressing disease-causing pathogens (Nikolić et al., 2026). Conversely, an overproduction of growth hormones by PGPR can suppress plant growth; these microbes can act as DRB. DRB can suppress plant growth through various mechanisms. These include the production of phytotoxins, hydrogen cyanide (HCN), lytic enzymes, exopolysaccharides (EPS), an increased level of indole-3-acetic acid (IAA), and 5-Aminolevulinic acid (ALA) (Beheshti et al., 2022; Dahiya et al., 2019; Phukan et al., 2021; Sindhu & Sehrawat, 2017). Crucially, certain rhizobacterial species may exhibit both functions; they can simultaneously function as DRB and can also stimulate plant growth by executing PGPR activities. This means they can simultaneously suppress weed growth while stimulating crop growth through nutrient uptake and phytohormone production.

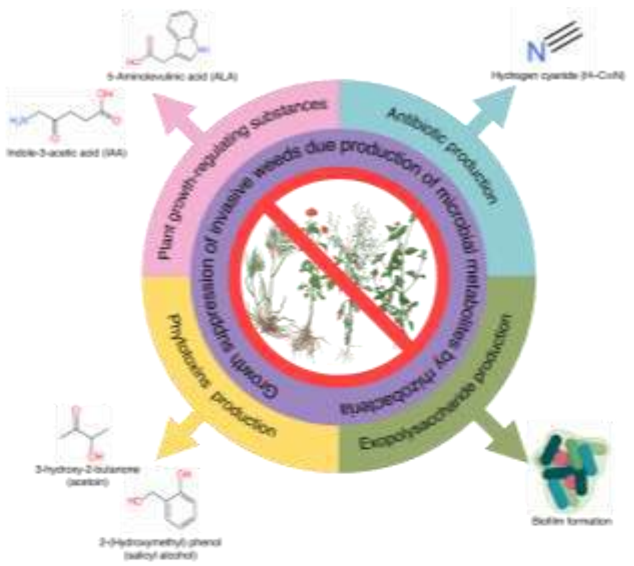

Fig. 2. Various microbial metabolites produced by microorganisms for weed control

Advantages of using rhizobacteria as a weed control are an environmentally friendly approach, suppresses weed growth, lowers weed resistance, and also lowers production cost. The number of studies revealed that the application of rhizobacteria is an environmentally friendly approach to impair the growth suppression of invasive weeds (Mishra & Nautiyal, 2012; Schroth & Hancock, 1982). The concept of biological weed control using rhizobacteria focuses on suppressing early weed growth just before the emergence of crop plants. This method prioritizes early competitive suppression rather than inducing endemic diseases in fully established weed plants (R. J. Kremer & Kennedy, 1996; Phukan et al., 2021). Consequently, rhizobacteria can suppress the early weed growth, giving the crops an advantage to outcompete the weakened weed seedlings. Utilizing rhizobacteria as biological weed control has huge potential, but moving this biocontrol ability of rhizobacteria out of the lab and into large-scale farming has not been explored. This review explores how rhizobacteria can act as a potential natural biological weed control while safeguarding agricultural yields.

II. MECHANISMS INVOLVED IN BIOLOGICAL WEED SUPPRESSION

2.1 Plant growth-regulating substances

Production of plant growth-regulators by rhizobacteria that colonize within the rhizosphere and can synthesize, release, and modulate phytohormones such as indole-3-acetic acid (IAA), 5-aminolevulinic acid (ALA), cytokinin, gibberellins, ethylene, and jasmonic acid (Kejela, 2024). Production of phytohormones is essential for regulating plant growth. Phytohormones also significantly influence the development of plant tolerance to a variety of biotic and abiotic stresses (Khan et al., 2020). Phytohormones play a key role in regulating numerous signal transduction pathways during the plant's response to abiotic stress, and regulate all cellular functions in plants (Khan et al., 2020; Pieterse et al., 2009).

1.1.1. Indole Acetic Acid (IAA)

Indole-3-acetic acid (IAA) is a primary auxin phytohormone that is essential for plant growth and development by regulating different physiological processes. Additionally, several rhizobacteria often produce this hormone. IAA stimulates plant growth at very low concentrations; in contrast, at higher concentrations, the effect may reverse, and elongation of roots and shoots is inhibited (Grossmann, 2010). The sensitivity to IAA is determined not just by concentration but also by the species of plant, physiological stage, and tissue. In response to elevated IAA levels, the plants show reduced elongation of internodes, inhibited root and shoot growth, enhanced green leaf pigmentation, closure of stomata, and an increase in reactive oxygen species (Grossmann, 2010). Rhizobacteria mainly produce IAA through tryptophan-dependent and tryptophan-independent mechanisms. The various IAA biosynthesis pathways have shown that bacterial and plant pathways are highly comparable. There are six different IAA biosynthetic bacterial pathways have been identified, five of them tryptophan-dependent (R. J. Kremer, 1999). Different rhizobacteria may harbour different IAA production pathways, and different bacterial species or strains may have varying levels of certain enzymes. Rhizobacteria can employ several pathways at once or alternate between them based on the availability of nutrients and environmental factors (Kejela, 2024).

Certain rhizobacterial strains present within the plant's rhizosphere release IAA, which enhances plant growth. Although IAA production causes cell wall loosening, which leaks plant nutrients for the growth of nearby microbes, while excessive release of IAA ultimately stunts plant development (Lindow & Brandl, 2003; Majda & Robert, 2018). An overproduction of IAA, it triggers the accumulation of aminocyclopropane-1-carboxylate (ACC), a direct metabolic precursor responsible for the formation of ethylene (Etesami & Glick, 2024). Certain rhizobacteria release high amount of high amount of IAA into the rhizosphere, which can suppress weed growth and inhibit root elongation (Sarwar & Kremer, 1995). As rhizobacteria colonize in the rhizosphere, their capacity to suppress plant growth is directly proportional to their microbial population, which in turn reflects the level of IAA production (Lindow & Brandl, 2003). (Kim & Kremer, 2005) noted that *Bacillus japonicum* isolate GD3 inhibited morning glory (*Ipomoea purpurea*), inhibited by IAA production.(Mejri et al., 2010) reported that the rhizobacterium *Pseudomonas trivialis* strain X33d suppresses the weed *Bromus diandrus* in the *Triticum durum* cropping system.

1.1.2. Aminolevulinic Acid (ALA)

5-Aminolevulinic acid (ALA) is a naturally occurring substance produced by many organisms. ALA is a pollution-free agrochemical that can also act as a bioherbicide (Nishihara et al., 2003; Rebeiz et al., 1984). ALA acts as a fundamental building block for the biosynthesis of tetrapyrroles, a process that enhances the growth and photosynthetic efficacy of agricultural produce (Sasaki et al., 1993). ALA is a photodynamic chemical that can serve as a feasible bioherbicide without causing any harm to crops, human health, and livestock (Bhowmick & Girotti, 2010; Kang et al., 2012; Sasikala et al., 1994; Sindhu & Sehrawat, 2017). When plants are treated with elevated levels of exogenous ALA (5-40 mM), it triggers bioherbicidal activity, causing several chlorophylls intermediate, including protoporphyrin IX and protochlorophyllide (Dahiya et al., 2019; Hotta et al., 1997). According to (Hotta et al. 1997), production of ALA at low concentrations improves crop yields, but at higher concentrations it may inhibit plant growth. (Khandelwal et al., 2018) Isolated 95 rhizobacterial strains from the rhizosphere of *Triticum aestivum* and *Brassica juncea,* significantly inhibiting the germination of *Chenopodium album* weed seeds in a laboratory plate assay. A lower concentration of ALA enhances the in vitro development of *Solanum tuberosum* microtuber and boosts protective mechanisms against oxidative stressors; however, ALA at high concentrations (30 mg L-1) and above could result in oxidative damage (Thompson et al., 2006).

2.2 Antibiotics

Antibiotics are lower-molecular-weight antimicrobial substances also produced by rhizobacteria, which are crucial for suppressing or inhibiting the growth of competing microbes and are essential for controlling phytopathogens. This mechanism is characterized by the antagonistic rhizobacteria through a process called antibiosis (Kenawy et al., 2019). *Azospirillum, Bacillus, Pseudomonas, Rhizobium,* and *Serratia* species are among the common rhizobacterial strains that can produce antibiotics and volatile organic compounds (Wang et al., 2021). Biosynthesis of antibiotics such as 2,4-diacetyl phloroglucinol (DAPG), hydrogen cyanide, and pyrrolnitrin is the primary mechanism of rhizobacteria for biocontrol (Kenawy et al., 2019). Different microorganisms synthesize a diverse range of antibiotics. For instance, rhizobacteria belonging to the *Bacillus* species produce several antimicrobial compounds, such as aminopolyols (zwittermicin A), bacillomycin D, fengycin, iturins, mycosubtilin, and surfactin (Kenawy et al., 2019). In contrast, fluorescent pseudomonads produce antibiotics including 2,4-diacetylphloroglucinol, pyoluteorin (Plt), phenazines, phenylpyrroles, pyrrolnitrin, oomycin A, viscosin, and massetolide A (Kenawy et al., 2019). Secretion of phenazine-1-carboxylic acid and 2,4-DAPG by Pseudomonas spp. can suppress the soilborne pathogen *Rhizoctonia solani* (Raaijmakers et al., 1997; Watrous et al., 2012).

2.3 Hydrogen cyanide (HCN)

Biosynthesis of volatile antibiotic hydrogen cyanide (HCN) can be considered a significant mechanism of rhizobacteria for the biological management of weeds. High concentrations of HCN suppress root respiration by blocking the cytochrome oxidase pathway. These metabolic pathways are vital for generating energy; their inhibition indirectly leads to poor nutrient absorption in the plant (SEHRAWAT et al., 2022). Biosynthesis of HCN in *Pseudomonas fluorescens* strains Q2-87 and CHA0 was found to be mediated by a defined hcnABC gene cluster. (Haas & Défago, 2005). Bacterial genera, such as *Pseudomonas*, are a major group of potential rhizobacteria capable of producing HCN. Studies have shown that the suppression of weeds in both laboratory and glasshouse trials, such as *Amaranthus spinosus* and *Portulaca oleracea,* due to HCN produced by *Pseudomonas aeruginosa* (Lakshmi et al., 2015). Under laboratory conditions, isolated *Xanthomonas* spp. can produce HCN as a secondary metabolite, which limits the development of *Parthenium hysterophorus* (Vishwas Shankar Patil, 2013). Establishment of HCN-producing rhizobacteria in the rhizosphere of weeds would be more economical than chemical synthesis or in-field application of growth-suppressive compounds (Alstr□m & Burns, 1989).

2.4 Exopolysaccharide (EPS)

Exopolysaccharides (EPS), which are bioactive extracellular polymeric substances produced by rhizobacteria, are becoming desirable choices for biocontrol of invasive weeds and for plant growth promotion (Jinisha et al., 2025; Tewari & Arora, 2014). These EPS-producing rhizobacteria are a particular type of PGPR. These microbes have diverse functions in improving soil structure, increasing nutrient uptake, and protecting plants from various environmental conditions (Celik et al., 2008; Jinisha et al., 2025). EPS are heteropolymers with an average molecular weight of 8×10^2 Da, which include a variety of monosaccharides, including xylose and arabinose, as well as functional groups, including hydroxyl, carboxyl, N-acetyl, amine, and sulphate esters (Jinisha et al., 2025; Sardari et al., 2017). It is produced by a variety of rhizobacteria as slime and capsular materials, which clay surfaces can absorb to provide a protective layer surrounding the aggregated soil (Jinisha et al., 2025; Yu et al., 2013). The production of EPS by microbes has been related to the virulence of pathogenic microbes. However, this mechanism has largely been neglected for rhizobacteria (Gnanamanickam, 2006; Pham et al., 2024). EPS producing rhizobacteria can enhance their ability to survive adverse environmental factors, such as high temperature and drought (Fett et al., 1989; R. J. Kremer, 2007). Recent studies show a strong correlation between the growth suppression of leafy spurge (*Euphorbia esula*) and elevated EPS production, together with other mechanisms of rhizobacteria, including the release of HCN and siderophore (R. Kremer et al., 2005; R. J. Kremer, 2007). EPS forms a dense, slimy layer and a moisture-rich matrix over a group of bacterial cells, forming a complex microenvironment called biofilm (Flemming et al., 2016).

2.4.1 Biofilm

Microbial biofilms are surface-attached bacterial cells enveloped in a self-synthesized matrix that predominantly contains proteins, polysaccharides, and lipids (Flemming & Wingender, 2010; Haque et al., 2020). The advantages of biofilm-forming rhizobacteria are because of their ability to resist antibiotics and adverse environmental pressures such as heat, drought, and high salinity, boosting their chances of surviving in adverse soil and environmental conditions (Haque et al., 2020). Biofilm-forming rhizobacteria also synthesize higher amounts of antimicrobial compounds, leading to suppression of weeds (Pandin et al., 2017). There are quite a few biofilm-forming species of rhizobacteria (e.g., *Agrobacterium sp., A. vinelandii, Bacillus subtilis*, *B. drentensis, Bradyrhizobium sp., Enterobacter cloacae, Pseudomonas sp., P. polymyxa, Rhizobium leguminosarum, Xanthomonas sp.*) that have been identified to date (Bais et al., 2004; Gupta et al., 2017; Haque et al., 2020; Mahmood et al., 2016; Timmusk et al., 2005). Quorum sensing plays a crucial role in regulating biofilm formation; it also controls the expression of virulence factors in pathogenic bacterial species (Gram et al., 2002; Mishra et al., 2015). Biofilm-forming rhizobacteria could be advantageous in the rhizosphere for weed control and also delivering beneficial effects to plants.

Several PGPR strains are known to form stable biofilms, including *Rhizobium leguminosarum*, *Agrobacterium* spp., *Pseudomonas* spp., *Bacillus subtilis*, and others. Recent studies have shown that PGPR exhibit notable resilience when exposed to allelochemicals released by *Parthenium hysterophorus*. For example, *Pseudomonas putida* NBRIC19 successfully developed biofilms in microtiter plate assays after three days of incubation, as measured by crystal violet staining, under both non-stress conditions (glucose-supplemented media) and stress conditions induced by various Parthenium-derived extracts. The strongest biofilm formation occurred in the presence of parthenin, indicating that the rhizobacterial strain's considerable adaptive capacity and tolerance to phytotoxic compounds produced by the invasive weed (Mishra & Nautiyal, 2012). (Mishra et al., 2012) reported that *P. putida* NBRIC19 enhanced the growth of *Triticum aestivum* in the presence of the allelochemical Parthenium. The presence of Parthenium caused *Triticum aestivum* to decrease in root and shoot length as well as dry biomass. However, this inhibition was effectively mitigated by P. putida NBRIC19, resulting in enhanced root development, shoot elongation, and overall dry weight compared to the control (Arnon, 1949; Mishra et al., 2012; Mishra & Nautiyal, 2012).

2.5 Phytotoxins

Production of phytotoxins is one such mechanism of action used by rhizobacteria to suppress plant growth. Few studies have shown that bacteria can produce phytotoxins for the suppression of invasive weeds. Numerous phytotoxins have been reported to disrupt plant metabolism, viz., by decreasing cell membrane integrity and macromolecule synthesis (Duke & Dayan, 2011). Several rhizobacterial strains were also found to synthesize a diverse range of phytotoxins and have the potential to serve as bioherbicides (Phukan et al., 2021). VOCs such as 2,3-butylene glycol and acetoin, produced by bacterial strains *Bacillus subtilis* and *Bacillus amyloliquefaciens*, stimulated plant growth, while HCN and benzenepropanoic acid can exhibit phytotoxicity, resulting in the suppression of plant growth when used in combination (Rath et al., 2018). The volatile compounds produced by rhizobacteria, such as 3-phenylpropionic acid and hydrogen cyanide (HCN), act in combination to suppress plant growth (R. J. Kremer & Souissi, 2001). (Adetunji et al., 2019) reported that bioactive phytotoxin produced by *Pseudomonas aeruginosa* strain C1501, with bioherbicidal activity, and the herbicidal compound has been identified as a salicyl alcohol. Root elongation in *Bromus tectorum* is suppressed by a specific complex of fatty acids, esters, and peptides, which is embedded in a lipopolysaccharide matrix synthesized by the *Pseudomonas fluorescens* strain D7 (Gurusiddaiah et al., 1994; Ibekwe et al., 2010; Tranel et al., 1993). According to (Gealy et al., 1996)*Pseudomonas syringae* strain 3366 suppressed the development of *Bromus tectorum* by producing the phytotoxins 1-phenazinecarboxylic acid, 2-aminophenoxazin-3-one, and 2-aminophenol.

III. CONCLUSION

The use of rhizobacteria for biocontrol of invasive weeds offers a promising and sustainable green alternative to chemical herbicides. This review underscores the potential of rhizobacterial strains to mitigate the severe 40-90% yield reductions caused by invasive weeds by colonizing the rhizosphere and deploying specific inhibitory mechanisms. The rhizosphere is a highly nutrient-dense zone for a diverse variety of soil microorganisms (Gray & Smith, 2005). In return, these soil microbes provide vital nutrients and growth factors for the development of plants, and some soil microbes secrete secondary metabolites that can suppress the growth of invasive weeds (Sindhu & Sehrawat, 2017). Depending upon their mode of action, rhizobacteria can function as PGPR or DRB, and some rhizobacteria may show both properties, offering a unique dual role in sustainable agriculture (Abbas et al., 2019; Phukan et al., 2021; Sindhu & Sehrawat, 2017). Through a variety of mechanisms, such as modulation of phytohormone, production of VOCs like hydrogen cyanide, phytotoxin production, antibiotic production, exopolysaccharide formation, and biofilm development, rhizobacteria can selectively suppress weed growth and improve crop production.

Several studies discussed in this review highlight the potential of bacterial strains such as *Pseudomonas, Bacillus*, and *Stenotrophomonas* to reduce the harmful effects of invasive weeds like *Parthenium hysterophorus* and *Bromus tectorum* while enhancing crop productivity. These findings demonstrate that rhizobacteria-based biocontrol of weeds could become an effective alternative to chemical herbicides and contribute significantly to sustainable agriculture.

However, despite focusing on laboratory and greenhouse results, more field trials are required to evaluate the consistency, survival, specificity, and ecological safety of these biocontrol agents under diverse environmental conditions. Although significant progress has been made in understanding rhizobacteria-mediated weed suppression, many underlying mechanisms and microbial interactions involved in biological weed control are still unexplored, and further investigation is required. Future research should focus on formulation development, field-level integration strategies, microbial interactions in the rhizosphere, and the application of rhizobacteria with other eco-friendly weed management approaches.

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