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Plant Growth-Promoting Rhizobacteria (PGPR) and Genetic Resistance: A Dual Approach to Crop Protection

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ABSTRACT

The increasing pressure on global agriculture from biotic stresses, diminishing soil fertility, and the overuse of chemical pesticides has driven the search for sustainable crop protection strategies. Among these, Plant Growth-Promoting Rhizobacteria (PGPR) and genetic resistance stand out as two highly promising and complementary approaches. PGPR enhance plant growth and health by facilitating nutrient acquisition, producing phytohormones, and activating plant defense responses, including induced systemic resistance. In parallel, advances in plant genetics—ranging from traditional breeding to modern gene-editing technologies—have enabled the development of disease-resistant cultivars with durable immunity against a wide range of pathogens. This review critically examines the mechanisms, benefits, and limitations of PGPR and host genetic resistance, and explores how their integration can provide a multifaceted, resilient, and environmentally sound solution for crop protection. Emphasis is placed on the molecular interactions, practical applications, and future directions for deploying these tools in tandem to support sustainable agricultural practices in the face of evolving global challenges.

Keywords: *PGPR, crop protection, genetic resistance, biocontrol, rhizosphere, induced systemic resistance, sustainable agriculture, plant immunity, biofertilizer, plant–microbe interaction.*

1. Introduction

Global agricultural systems are under increasing pressure to produce more food while minimizing environmental degradation and ensuring sustainability. Among the most formidable challenges facing modern agriculture are crop losses due to pests, diseases, and environmental stresses [1]. It is estimated that up to 40% of global crop yields are lost annually to plant pathogens, insects, and weeds, posing a major threat to food security, especially in regions already struggling with resource scarcity. Historically, the dominant approach to managing these losses has involved the use of chemical pesticides and fertilizers. While effective in the short term, these inputs have come under scrutiny due to their negative impacts on soil health, non-target organisms, environmental pollution, and human health. Moreover, the excessive use of agrochemicals has contributed to the emergence of resistant pathogen strains and pest populations, further exacerbating the problem [2-3]. As a result, there is growing interest in alternative and integrated crop protection strategies that are both environmentally friendly and economically viable. Two such strategies gaining prominence are the use of Plant Growth-Promoting Rhizobacteria (PGPR) and genetic resistance. These approaches, when applied synergistically, offer a promising route toward sustainable crop production [4].

PGPR are a diverse group of beneficial soil bacteria that colonize plant roots and exert positive effects on plant growth and health. Their modes of action are multifaceted and include nitrogen fixation, phosphorus solubilization, production of phytohormones such as auxins and gibberellins, suppression of plant pathogens through the production of antibiotics and siderophores, and the activation of plant defense mechanisms such as Induced Systemic Resistance (ISR). Notable genera include *Pseudomonas*, *Bacillus*, *Azospirillum*, and *Rhizobium*, among others [5-6]. These bacteria not only enhance plant productivity under normal conditions but also improve tolerance to abiotic stresses like drought, salinity, and heavy metal toxicity.

Parallel to the development of microbial-based solutions, significant advances have been made in plant genetics and breeding for disease resistance. Genetic resistance involves the identification, incorporation, and manipulation of resistance (R) genes that enable plants to recognize and counteract specific pathogens [7]. Classical breeding techniques have been used for decades to develop resistant cultivars through selection and cross-breeding. More recently, molecular breeding and gene-editing technologies such as CRISPR/Cas9 have revolutionized the field, allowing for precise and rapid enhancement of resistance traits. These genetic tools enable the targeting of specific pathways involved in pathogen recognition, signaling, and response, thereby enhancing the durability and spectrum of resistance. Despite their individual benefits, PGPR and genetic resistance strategies are often pursued in isolation. However, increasing evidence suggests that an integrated approach combining both biological and genetic tools can result in synergistic effects that offer enhanced and durable protection

against a wide array of pathogens [8]. For instance, PGPR can prime plant immune systems, making resistance genes more effective upon pathogen attack. Additionally, resistant cultivars can provide a stable environment for PGPR colonization and activity, fostering a mutual reinforcement between plant and microbe.

This integrated strategy aligns with the principles of Integrated Pest Management (IPM) and sustainable agriculture, aiming to minimize chemical inputs while maximizing natural resistance mechanisms. Furthermore, it supports the development of resilient agroecosystems that can better withstand the uncertainties of climate change and evolving pathogen populations [9-11]. This review aims to present a comprehensive exploration of the roles and mechanisms of PGPR in plant growth promotion and disease suppression, as well as the current state and advances in genetic resistance to crop pathogens. It will also discuss how these two approaches can be effectively combined to create robust, sustainable crop protection systems. Key topics covered include the taxonomy and functional traits of PGPR, signaling pathways involved in plant-microbe interactions, the identification and deployment of R-genes, and case studies demonstrating the success of integrated strategies in field conditions [12-13]. By synthesizing current knowledge and identifying areas for future research, this review seeks to provide a scientific foundation for developing next-generation crop protection methods that are ecologically sound, economically feasible, and globally applicable.

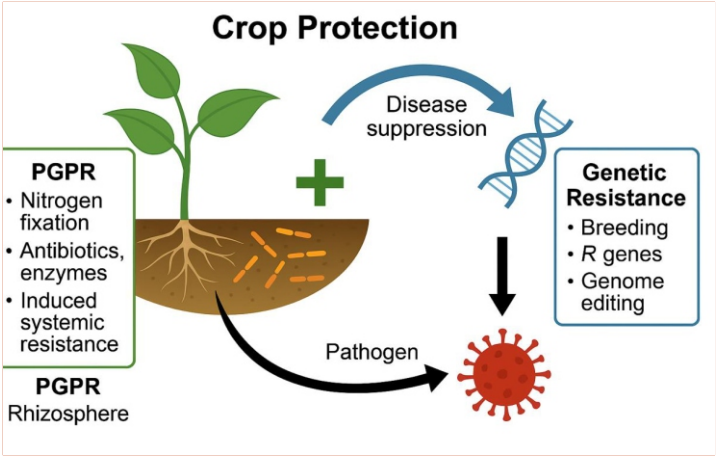

Figure 1. The image illustrates the synergistic role of Plant Growth-Promoting Rhizobacteria (PGPR) and genetically resistant plants in enhancing crop protection. It highlights mechanisms such as root colonization, ISR induction, and R gene-mediated defense.

2. Plant Growth-Promoting Rhizobacteria (PGPR): Mechanisms and Applications

Plant Growth-Promoting Rhizobacteria (PGPR) are a group of beneficial soil bacteria that colonize the rhizosphere—the zone of soil surrounding plant roots—and positively influence plant development and health. Their functions can be broadly categorized into direct growth promotion, indirect growth enhancement through disease suppression, and dynamic interactions within the rhizosphere ecosystem [14]. These multifaceted mechanisms have made PGPR a cornerstone of sustainable agriculture and integrated crop protection strategies.

2.1 Direct Growth Promotion

PGPR directly promote plant growth by enhancing nutrient acquisition and modulating phytohormone levels. A key mechanism is biological nitrogen fixation, in which nitrogen-fixing bacteria such as *Azospirillum*, *Azotobacter*, and *Rhizobium* convert atmospheric nitrogen (N_2) into ammonia (NH_3), making this essential nutrient bioavailable for plants. In leguminous crops, symbiotic interactions with *Rhizobium* species result in root nodule formation and efficient nitrogen fixation, significantly reducing the need for synthetic fertilizers [15-17]. Another vital contribution of PGPR is phosphate solubilization. Many soil phosphates exist in insoluble forms that are inaccessible to plants. PGPR such as *Pseudomonas* and *Bacillus* produce organic acids and phosphatases that convert these compounds into soluble forms, thereby enhancing phosphorus availability. Additionally, PGPR synthesize plant hormones like indole-3-acetic acid (IAA), cytokinins, and gibberellins, which regulate root architecture, cell elongation, and overall plant vigor. This hormonal modulation often leads to increased root surface area and improved nutrient uptake.

2.2 Indirect Growth Promotion and Biocontrol

In addition to their direct effects, PGPR play a crucial role in suppressing plant pathogens and enhancing plant immunity. One of the primary mechanisms involves the production of siderophores, iron-chelating compounds that deprive pathogenic microbes of essential iron, thereby inhibiting their proliferation. PGPR also produce antibiotic compounds, such as phenazines, pyrrolnitrin, and 2,4-diacetylphloroglucinol, which have strong antagonistic activity against fungal and bacterial pathogens [18-19]. Another indirect mechanism involves the secretion of hydrolytic enzymes like chitinases, glucanases, and proteases, which degrade the structural components of fungal cell walls and inhibit pathogen invasion. Perhaps most significantly, PGPR can trigger Induced Systemic Resistance (ISR) in plants. Unlike systemic acquired resistance (SAR), which is initiated by pathogen infection, ISR is activated preemptively by beneficial microbes. This “priming” enhances the plant's readiness to respond to future attacks through the upregulation of defense-related genes and pathways without the energy cost associated with constant immune activation.

2.3 Colonization and Rhizosphere Dynamics

The effectiveness of PGPR in promoting growth and controlling disease largely depends on their ability to colonize the rhizosphere and establish stable associations with plant roots. Successful colonization is influenced by multiple factors, including the composition of root exudates, microbial competitiveness, soil conditions, and plant genotype. Root exudates provide chemical signals and nutrients that attract beneficial microbes, shaping the microbial community in the rhizosphere [20-21]. A critical factor in effective colonization is biofilm formation, which enhances microbial persistence under environmental stress and facilitates strong root adherence. Within biofilms, PGPR are protected from desiccation, predation, and antimicrobial agents, thereby improving their stability and functionality in the soil environment. The dynamic interactions within the rhizosphere—between PGPR, pathogens, the host plant, and other soil microbes—constitute a complex ecological network that ultimately determines the success of PGPR-based interventions.

3. Genetic Resistance in Plants

Genetic resistance in crops is a foundational strategy for achieving long-term, sustainable disease management. This approach relies on enhancing the plant's intrinsic ability to recognize and respond to pathogenic threats, thereby reducing reliance on chemical pesticides and limiting crop losses [22]. Over time, advances in both classical breeding and modern molecular techniques have significantly broadened the scope and effectiveness of genetic resistance strategies.

3.1 Classical and Molecular Breeding

Historically, plant breeders have utilized phenotypic selection to identify individuals with desirable resistance traits, followed by crossbreeding to introduce these traits into elite cultivars. While effective, this method is time-consuming and often hindered by the influence of environmental variability on disease expression. The advent of molecular breeding, particularly marker-assisted selection (MAS), has accelerated the development of resistant varieties by enabling the identification and tracking of specific genetic loci associated with disease resistance [23]. By using DNA markers tightly linked to resistance (R) genes, breeders can screen for resistant genotypes with greater precision, even before symptoms appear. This approach reduces the breeding cycle time and increases the efficiency of incorporating resistance traits into diverse genetic backgrounds.

3.2 Resistance (R) Genes and Pathogen Recognition

Central to genetic resistance are Resistance (R) genes, which encode proteins that detect specific pathogen-derived molecules, known as effectors. Upon recognition, these R proteins initiate a hypersensitive response (HR)—a localized cell death at the infection site—along with the activation of systemic acquired resistance (SAR) to protect uninfected tissues. Most R proteins belong to the nucleotide-binding site leucine-rich repeat (NBS-LRR) class, which plays a crucial role in innate immunity across plant species. For instance, *Xa21*, an R gene in rice, confers resistance against *Xanthomonas oryzae* (the causal agent of bacterial blight), while *RPS2* in *Arabidopsis thaliana* provides defense against *Pseudomonas syringae* strains carrying the effector protein AvrRpt2 [24]. The deployment of such R genes has enabled the development of disease-resistant cultivars in major crops, but their effectiveness may wane over time due to evolving pathogen virulence.

3.3 Genetic Engineering and Genome Editing

To overcome the limitations of natural variation and evolutionary arms races with pathogens, genetic engineering has enabled the transfer of resistance traits across species boundaries. For example, the introduction of *Bacillus thuringiensis* (Bt) genes into crops like maize and cotton has provided durable resistance to insect pests, significantly reducing pesticide use. More recently, genome editing technologies such as CRISPR/Cas9 have revolutionized plant biotechnology by allowing precise, targeted modifications in the genome. These tools can be employed to knock out susceptibility (S) genes, which pathogens exploit to facilitate infection, thereby enhancing resistance without introducing foreign DNA. Alternatively, CRISPR can be used to engineer or enhance R genes to recognize a broader range of pathogen effectors or to fine-tune their regulatory elements for optimal expression [26-26]. The integration of gene-editing technologies into crop improvement pipelines offers unprecedented flexibility and speed in developing resistant varieties. However, careful evaluation of off-target effects, regulatory frameworks, and public acceptance remains essential for their widespread adoption.

Table 1: An Important Mechanisms of PGPR in Plant Growth and Disease Suppression

Mechanism	Description	Representative PGPR Examples
Nitrogen fixation	Conversion of atmospheric nitrogen into plant-usable forms	*Azotobacter*, *Rhizobium*, *Azospirillum*
Phosphate solubilization	Transformation of insoluble phosphates into bioavailable forms	*Pseudomonas*, *Bacillus*, *Enterobacter*
Phytohormone production	Synthesis of auxins, cytokinins, gibberellins to promote plant development	*Bacillus subtilis*, *Azospirillum*
Siderophore production	Chelation of iron, limiting pathogen access	*Pseudomonas fluorescens*, *Bacillus*
Antibiotic production	Release of antimicrobial compounds	*Streptomyces*, *Pseudomonas*, *Bacillus*
Induced systemic resistance	Priming plant defense responses via JA/ET pathways	*Bacillus amyloliquefaciens*, *Serratia*

Table 2: Categories of Genetic Resistance in Plants

Type of Resistance	Basis	Examples
Qualitative (Monogenic)	Single R gene; often race-specific	*Xa21* (rice), *RPS2* (Arabidopsis)
Quantitative (Polygenic)	Multiple genes; broad-spectrum, durable	Multiple QTLs in wheat for rust resistance
Transgenic Resistance	Introduction of resistance genes from other species	Bt cotton, virus-resistant papaya
Genome-Edited Resistance	CRISPR/Cas-mediated modification of S or R genes	Knockout of *MLO* gene for powdery mildew

Table 3: Advantages of Integrating PGPR and Genetic Resistance

Aspect	Benefit
Defense pathway complementation	Combines JA/ET-mediated ISR (via PGPR) with SA-mediated SAR
Reduced selection pressure	Slows pathogen evolution by minimizing direct biocidal activity
Enhanced resistance durability	Synergistic effect reduces the likelihood of resistance breakdown
Lower chemical input	Minimizes pesticide and fertilizer use
Environmental sustainability	Promotes biodiversity and soil health

4. Synergy Between PGPR and Genetic Resistance

An emerging paradigm in sustainable crop protection is the combined use of Plant Growth-Promoting Rhizobacteria (PGPR) and genetic resistance [27]. While both strategies individually offer effective mechanisms to enhance plant immunity and reduce pathogen impact, their integration can provide a more robust and resilient defense system. Recent research highlights that the interaction between microbial inoculants and plant immune pathways can be complementary, synergistic, and, in some cases, mutually reinforcing.

4.1 Complementary Defense Layers

PGPR and genetically encoded resistance mechanisms activate distinct but partially overlapping defense signaling pathways. PGPR primarily trigger Induced Systemic Resistance (ISR), which is mediated through the jasmonic acid (JA) and ethylene (ET) pathways. In contrast, genetically driven resistance, especially that conferred by Resistance (R) genes, relies on Systemic Acquired Resistance (SAR), predominantly regulated by the salicylic acid (SA) pathway [28]. These pathways do not function in isolation; instead, they exhibit complex cross-talk that can lead to additive or even synergistic effects. The activation of ISR by PGPR primes the plant to respond more rapidly and effectively to pathogen attack, whereas R genes provide specificity and direct recognition of pathogen effectors. The simultaneous activation of both pathways can provide a multilayered defense system, offering broader spectrum and more durable resistance.

4.2 Enhancing Resistance Durability

One of the major challenges in deploying genetic resistance is the risk of **resistance breakdown** due to pathogen evolution. Pathogens may overcome single-gene resistance through mutations or gene loss, rendering formerly resistant cultivars vulnerable. PGPR can help mitigate this risk by exerting biocontrol effects that do not impose the same selection pressures as lethal chemical or genetic interventions. Since ISR involves priming the plant's defenses rather than directly killing pathogens, it creates a less antagonistic environment that reduces the likelihood of resistance development in pathogen populations. Consequently, PGPR application in fields with resistant cultivars may help prolong the effectiveness of R genes by diversifying the plant's defensive arsenal and reducing the evolutionary incentives for pathogens to adapt.

4.3 PGPR as Modulators of Plant Gene Expression

Another layer of interaction arises from the ability of PGPR to modulate plant gene expression, including genes involved in innate immunity. Several studies have demonstrated that PGPR strains can upregulate the expression of R genes and other defense-related genes, thereby enhancing the basal and inducible resistance levels of host plants. This gene expression modulation can amplify existing genetic resistance and improve the plant's overall responsiveness to biotic stress. Additionally, PGPR can influence hormonal signaling cascades and transcription factors that interact with both ISR and SAR pathways, further integrating microbial and genetic resistance mechanisms. This regulatory plasticity underscores the potential of PGPR to act not just as microbial antagonists, but as sophisticated modulators of the plant immune network [29], combining PGPR with genetically resistant cultivars offers a holistic, sustainable, and potentially more durable strategy for crop protection.

Future research should focus on unraveling the molecular underpinnings of these interactions, optimizing combinations of specific PGPR strains and R genes, and testing their performance across different agroecosystems.

6. Challenges and Limitations

Despite the promising potential of integrating Plant Growth-Promoting Rhizobacteria (PGPR) and genetic resistance in crop protection, several challenges must be addressed to ensure the success and scalability of this dual approach [30]. These limitations stem from biological variability, environmental interactions, technological constraints, and regulatory considerations.

6.1 PGPR Variability and Environmental Influence

One of the major challenges in PGPR application is the variability in performance across different soil types, climates, and cropping systems. The efficacy of a PGPR strain can be highly context-dependent, influenced by soil pH, organic matter content, temperature, moisture, and microbial community composition. A strain that promotes plant growth in one environment may show negligible or even negative effects in another. This environmental sensitivity limits the consistency of field outcomes and requires region-specific strain selection, formulation, and testing.

6.2 Compatibility with Plant Genotypes

Another limitation lies in the genotype-specific interactions between PGPR and host plants. Not all PGPR strains exhibit broad-spectrum compatibility with different crop cultivars. Some strains may colonize one genotype effectively but fail to associate or provide benefits to another. These host-specific effects necessitate co-optimization of PGPR strains with particular crop varieties, which can complicate breeding programs and increase the cost and time required for field deployment.

6.3 Regulatory and Public Acceptance Barriers

Both PGPR-based bioproducts and genetically modified (GM) crops face significant regulatory hurdles in many countries. While microbial inoculants are typically subject to biosafety evaluations for environmental impact and human health, the approval process can be lengthy and variable across jurisdictions. Similarly, genetically engineered crops—especially those involving transgenic or gene-editing technologies—remain controversial in certain regions due to concerns about ecological risks, food safety, and corporate control over seeds. These regulatory and socio-political barriers can delay or prevent the adoption of innovative, integrated crop protection solutions [31].

6.4 Pathogen Evolution and Resistance Breakdown

Even with the integration of PGPR and genetic resistance, pathogens may continue to evolve, eventually overcoming the multilayered defense system. High mutation rates, horizontal gene transfer, and selection pressure in monoculture systems can enable pathogens to bypass R gene recognition or develop tolerance to PGPR-mediated suppression. Therefore, relying solely on these two approaches without incorporating agroecological diversification, crop rotation, and disease surveillance may not be sufficient for long-term sustainability.

7. Future Perspectives

The integration of Plant Growth-Promoting Rhizobacteria (PGPR) and genetic resistance represents a forward-looking, ecologically sound paradigm for sustainable crop protection. However, unlocking the full potential of this dual strategy requires advancements in both conceptual frameworks and technological platforms. Several emerging directions offer promising pathways to enhance the consistency, scalability, and precision of integrated disease management systems.

7.1 Holobiont Breeding: Co-selecting Plants and Microbiomes

A transformative concept in modern plant science is the recognition of the plant holobiont, which views the host plant and its associated microbial communities as a unified biological entity. This perspective encourages breeding not only for plant traits but also for traits that promote beneficial interactions with the rhizosphere microbiome, including PGPR. Holobiont breeding could enable the selection of cultivars with enhanced capacities to recruit, support, and respond to effective PGPR, resulting in improved resilience to biotic stresses. This approach also underscores the importance of preserving microbial diversity and functionality in agricultural soils.

7.2 Precision Agriculture and Omics Technologies

The application of omics tools—such as metagenomics, transcriptomics, proteomics, and metabolomics—offers unprecedented insights into plant–microbe interactions and resistance signaling pathways. Metagenomics can reveal the structure and function of rhizosphere microbial communities in different soil environments, identifying PGPR strains associated with disease suppression or growth promotion. Meanwhile, transcriptomic and metabolomic analyses can uncover molecular cross-talk between PGPR and host plants, guiding the design of targeted bioinoculants and resistance traits. These insights, when coupled with precision agriculture technologies such as site-specific inoculant application and sensor-based monitoring, can greatly enhance the effectiveness and adaptability of integrated protection systems.

7.3 Development of Formulated Bioinoculants

To overcome the inconsistency of PGPR performance in the field, there is a growing focus on the development of standardized, formulated consortia comprising multiple compatible PGPR strains with complementary traits. These consortia can provide broader-spectrum protection, increase ecological fitness across variable soil conditions, and reduce dependency on single-strain efficacy. Advances in formulation technology, including encapsulation and carrier systems, are improving the shelf life, delivery, and colonization success of bioinoculants. Furthermore, formulations may be tailored to specific crop genotypes and environmental conditions, enhancing compatibility and repeatability of results.

7.4 Synthetic Biology and Engineered Microbiomes

Synthetic biology offers a frontier for designing customized PGPR with enhanced or novel functions, such as the ability to sense plant stress signals and respond with targeted antimicrobial production. Engineered PGPR could also carry genetic circuits that activate plant immunity pathways on demand or express quorum-quenching enzymes that disrupt pathogen communication. Additionally, synthetic microbial consortia—designed through computational modeling and metabolic engineering—can be assembled to function cooperatively in plant protection. While regulatory and ecological safety considerations remain critical, these innovations hold promise for next-generation biocontrol solutions that are both intelligent and adaptable.

8. Conclusion

The integration of Plant Growth-Promoting Rhizobacteria (PGPR) and genetic resistance offers a synergistic and environmentally sustainable strategy for enhancing crop protection in modern agriculture. PGPR contribute to plant health not only by promoting growth through nutrient acquisition and hormone production but also by triggering indirect defense mechanisms such as induced systemic resistance. Simultaneously, genetically resistant cultivars provide a foundational line of defense against specific pathogens through innate immune responses mediated by resistance (R) genes and molecular signaling pathways. When combined, these two approaches can provide multilayered protection that is more durable and resilient than either strategy alone. The complementary nature of PGPR and plant genetic resistance helps mitigate the risk of pathogen adaptation and reduces dependence on chemical pesticides, thereby contributing to both environmental safety and long-term productivity, advances in genomics, high-throughput phenotyping, microbiome engineering, and synthetic biology hold promise for optimizing this integrated approach. Innovations such as holobiont breeding, precision application of bioinoculants, and the deployment of engineered microbial consortia will further enhance efficacy and consistency across diverse agroecological contexts. Ultimately, harnessing the full potential of PGPR and genetic resistance in tandem is essential for developing resilient agroecosystems capable of meeting global food security challenges while maintaining ecological balance.

Author Statement

The authors declare that there is no conflict of interest regarding the publication of this manuscript and have contributed significantly to the work and have approved the final version of the manuscript.

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